Interagency Flood Risk Management (InFRM)

Hydrology Report for the

San Marcos River Basin

Prepared by: U.S. Army Corps of Engineers, Fort Worth District
Submitted to: Federal Emergency Management Agency (FEMA) Region VI

Published Date: September 15, 2016

Table of Contents

Template: January 5, 2016

Executive Summary

The National Flood Insurance Program (NFIP) was created in 1968 to guide new development (and construction) away from flood hazard areas and to help transfer the costs of flood damages to the property owners through the payment of flood insurance premiums. The Federal Emergency Management Agency (FEMA) administers the NFIP. The standard that is generally used by FEMA in regulating development and in publishing flood insurance rate maps is the 1% annual chance (100-yr) flood. The 100-yr flood is defined as a flood which has a 1% chance of happening in any year. The factor that has the greatest influence on the depth and width of the 100-yr flood zone is the expected 1% annual chance (100-yr) flow value.

This report summarizes new analyses that were completed to estimate the 1% annual chance (100-yr) flow, along with other frequency flows, for various stream reaches in the San Marcos River Basin. These analyses are part of a larger study being conducted for FEMA Region VI by an Interagency Flood Risk Management (InFRM) team. InFRM includes subject matter experts (SME) from the U.S. Army Corps of Engineers (USACE), the U.S. Geological Survey (USGS), and the National Weather Service (NWS). The InFRM team is using several different methods, including statistical hydrology and rainfall-runoff watershed modeling, to calculate the 1% annual chance (100-yr) flow and is then comparing those results to each other. The purpose is to produce 100-yr flow values that are consistent and defendable across the basin.

The 1% annual chance (100-yr) flows that are on the currently effective flood insurance rate maps in Hays County (FEMA, 2005), which includes the cities of Wimberley and San Marcos and a large portion of the San Marcos River Basin, were based on regression equations that were published in a USGS report in 1995 (Slade, 1995). A regression equation is a method that allows for calculation of the 1% annual chance (100-yr) flow with very little information about the watershed. The Hays County regression equation requires only two variables (the slope of the river and the area of the watershed) to calculate the 1% flow. However, this method has its drawbacks.

The equation for the 1% annual chance (100-yr) flow was developed by drawing a “best fit” curve through 100-yr flow points that were estimated at a number of sites across the region. The accuracy of that equation depends first on the precision of the estimated 100-yr flow points. For Hays County, the 100-yr flow points were estimated based on a statistical analysis of the available stream gage records through the year 1992. However, several major floods have occurred in the San Marcos basin since then, which drastically change statistical estimates of the 1% annual chance (100-yr) flow. For example, since 1998, there have been five major floods that have exceeded a flow of 70,000 cubic feet per second (cfs) in magnitude at Wimberley, Texas; whereas the 70 years prior to 1998 saw only three floods greater than 70,000 cfs, as illustrated in Figure ES.1. The limited period of record that was available during the early 1990s would have caused the 1% annual chance (100-yr) flow values from that time to be underestimated.

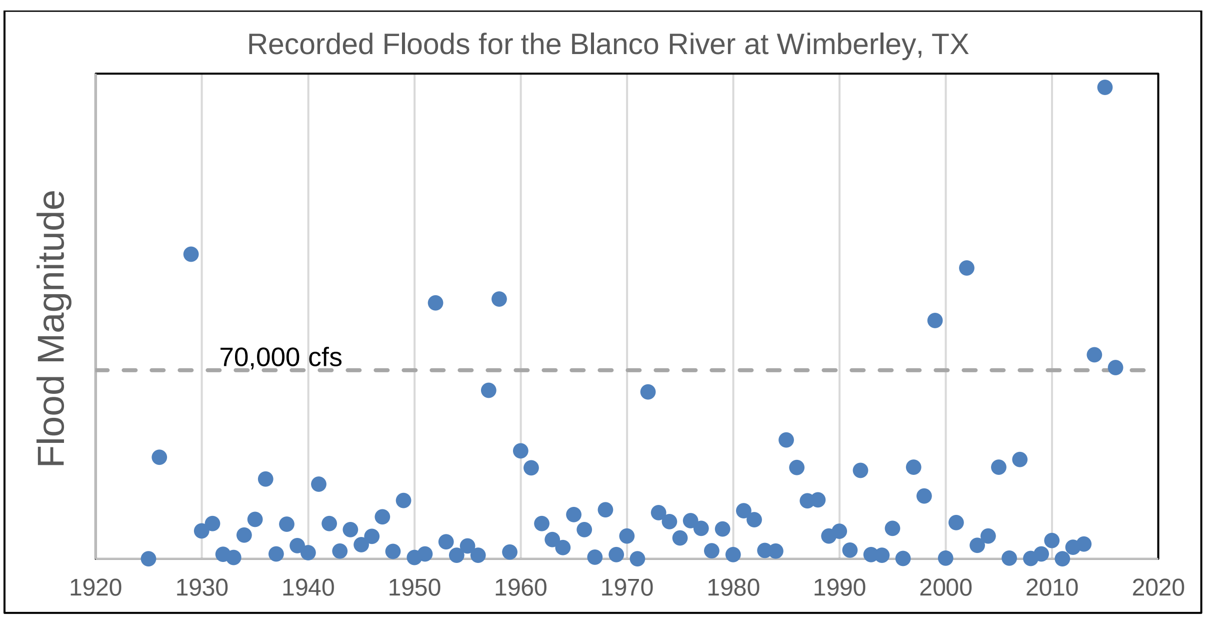

Figure ES.1: Recorded Floods from 1925-2016 for the Blanco River at Wimberley, TX

This trend is shown even more dramatically in Figure 2 for the San Marcos River at Luling, Texas. Prior to 1998, the largest flood on record at Luling was 57,000 cfs. Post 1998, there have been four major flood events that were much larger than all prior recorded floods, the largest being the 1998 flood with a flow of 206,000 cfs. This further illustrates that the 1% annual chance (100-yr) flows that are on the currently effective maps were likely underestimated.

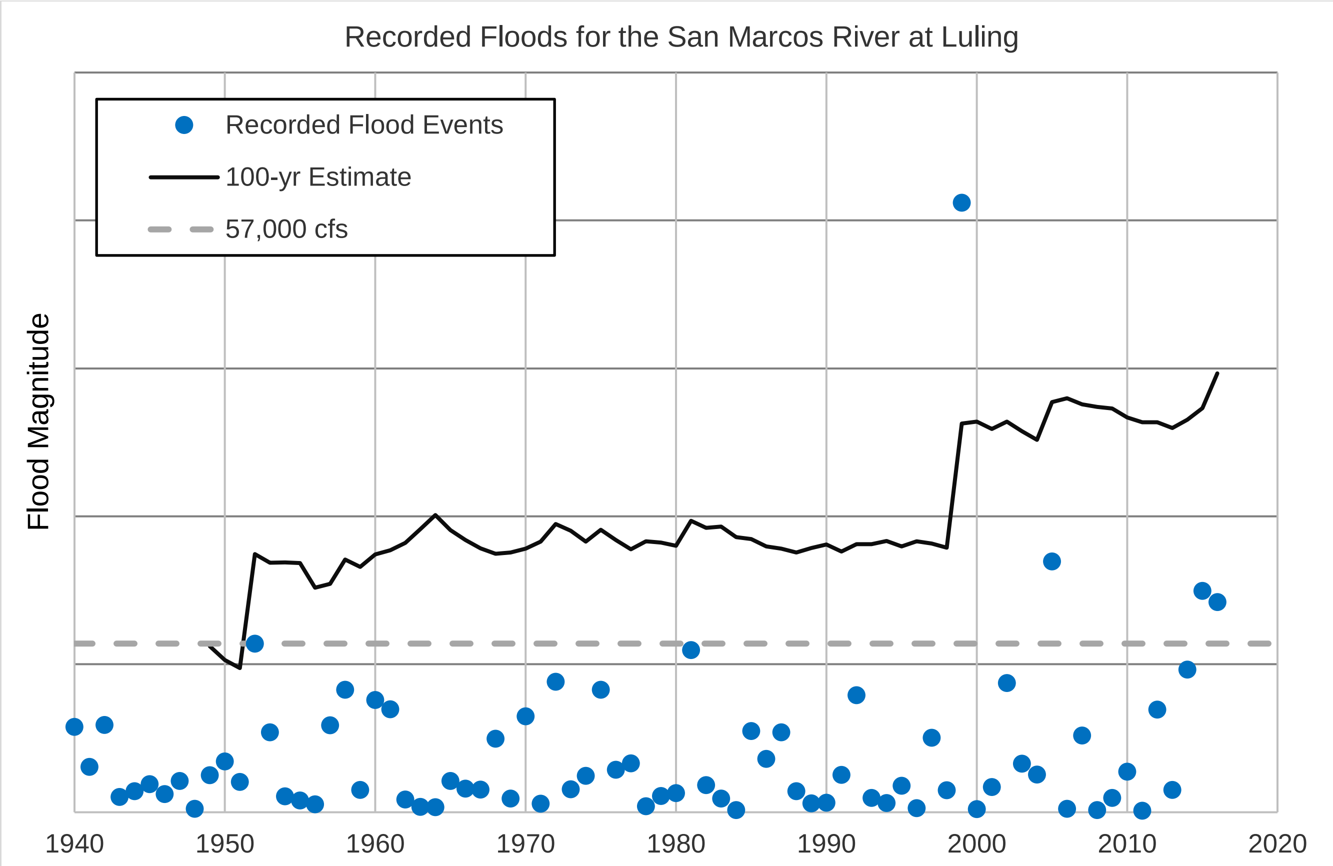

Figure ES.2: Recorded Floods from 1940-2016 for the San Marcos River at Luling, TX

By contrast, in the current study, the InFRM team used both up-to-date statistical analysis and state-of-the-art rainfall-runoff watershed modeling to estimate the 1% annual chance (100-yr) flow values throughout the San Marcos River Basin. In the statistical analysis, the gage records were updated through the year 2016 to include all recent major flood events. However, since statistical estimates inherently change with each additional year of data, their results were compared to the results of a detailed watershed model which is less likely to change over time.

Rainfall-runoff watershed modeling is used to simulate the physical processes that occur during storm events to simulate how water moves across the land surface and through the streams and rivers. A watershed model was built for the San Marcos River Basin with input parameters that represented the physical characteristics of the watershed. After building the model, the InFRM team calibrated the model to verify it was accurately simulating the response of the watershed to a range of observed flood events, including large events similar to a 1% annual chance (100-yr) flood. A total of eight recent storm events were used to fine tune the model, as shown in Table ES.1.

Table ES.1: Flood Events Simulated in the San Marcos Watershed Model

Date of Flood	Recorded Peak Flow (cfs)		
	Blanco River at Wimberley	Blanco River near Kyle	San Marcos River at Luling
Oct-1998	88,500	105,000	206,000
Nov-2001	108,000	87,300	43,700
Nov-2004	34,000	31,600	84,800
Mar-2007	36,900	34,500	25,900
Jan-2012	-	-	34,700
Oct-2013	75,800	101,000	48,200
May-2015	175,000	180,000	74,800
Oct-2015	71,000	115,000	71,000

For these storms, the availability of National Weather Service (NWS) hourly rainfall radar data allowed for more detailed fine tuning of the watershed model than would have been possible during earlier modeling efforts. The model calibration and verification process undertaken during this study substantially exceeds the standard of a typical FEMA floodplain study. The final model results accurately simulated the expected response of the watershed, as it reproduced the timing, shape, and magnitudes of the observed floods very well. An example plot of the modeled flow versus the recorded flow is shown on Figure ES.3, but many other similar figures are available in Chapter 6 of this report.

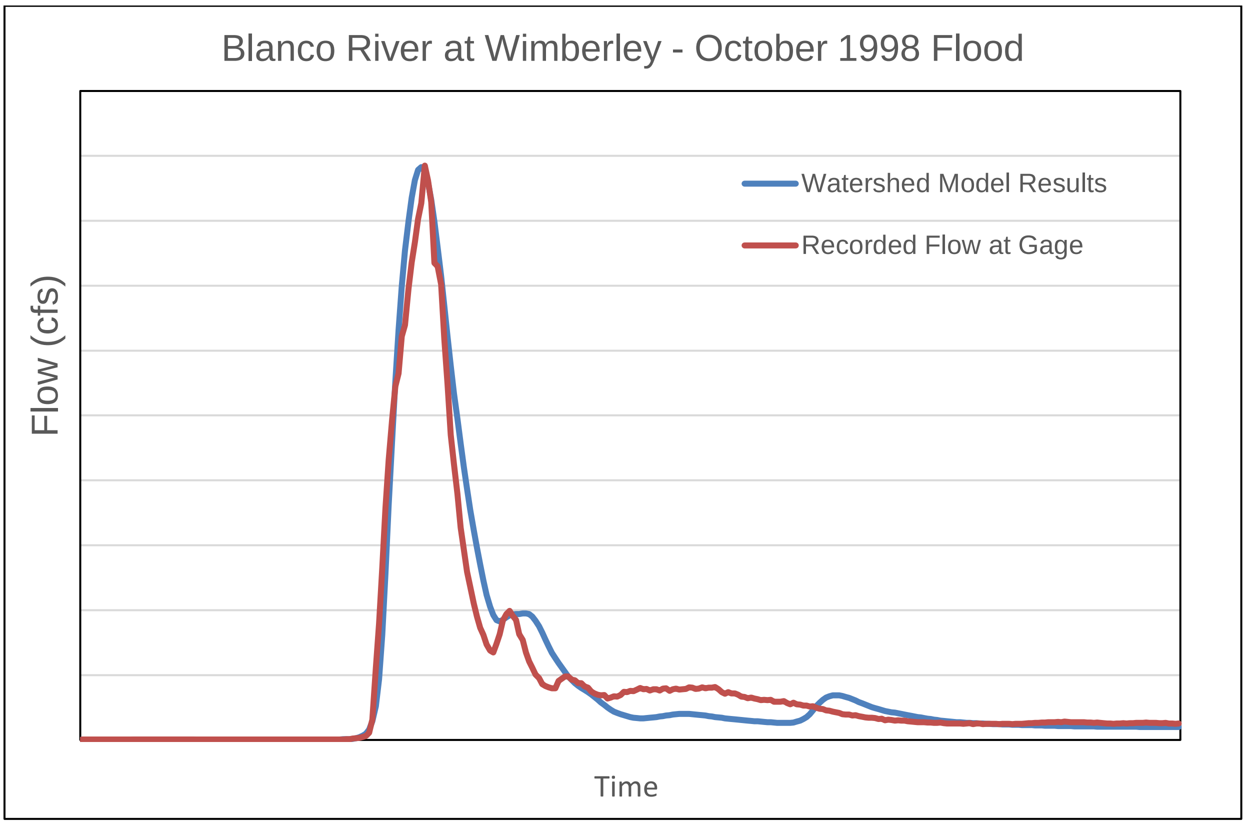

Figure ES.3: Example Watershed Model Results versus Recorded Flow

The 1% annual chance (100-yr) flow values were then calculated by applying the 100-yr rainfall to the watershed model. Rainfall estimates for the 100-yr storm are considered more reliable than statistical estimates for the 100-year flow due to the larger number of rainfall stations and the longer periods of time during which rainfall measurements have been made. After completing the model runs, the watershed model results were compared to the statistical analysis results and the effective FEMA flows, as shown in Table ES.2 and in Figure ES.4.

Table ES.2: Summary of 1% annual chance (100-yr) Flow Results (cfs)

Location	Currently Effective Flow*	Statistical Analysis	Watershed Model	Recommended Flow
Blanco River at Wimberley	112,800	153,700	152,600	152,600
Blanco River near Kyle	122,600	170,400	153,900	153,900
San Marcos River at Luling	110,000	143,600	142,400	142,400

*Hays County FEMA Flood Insurance Study Effective September 2005

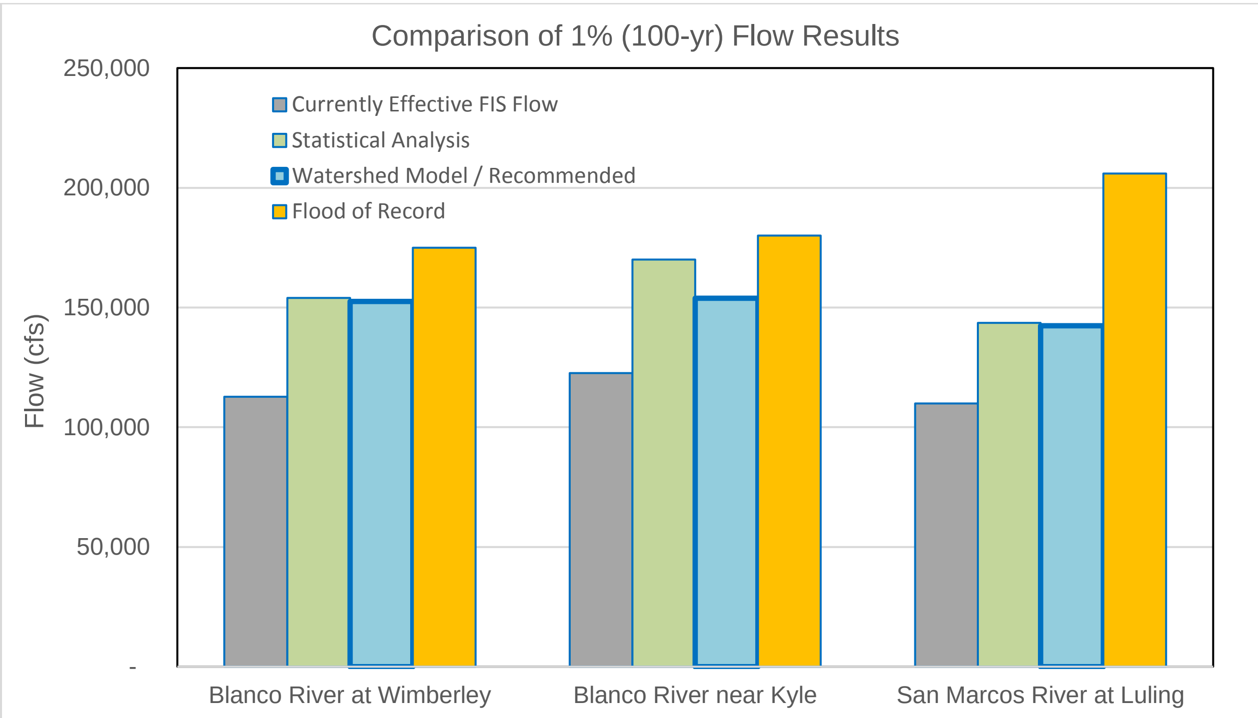

Figure ES.4: Comparison of 1% annual chance (100-yr) Flow Results

In conclusion, the statistical analysis and the watershed model displayed agreement with each other; however, the watershed model results were slightly lower than the statistical results. Both sets of results were significantly higher than the flows on the currently effective flood insurance rate maps. After reviewing the available information and analyses, the watershed model results were selected as the recommended flows for the San Marcos River Basin. The new flows represent the best estimate of flood risk for the Blanco River, San Marcos River, and Plum Creek based on a range of hydrologic methods performed by an expert team of engineers and scientists from multiple federal agencies. For the smaller tributaries, the new flows from the watershed model provide a good starting point which could be further refined by adding additional subbasins and using methodologies that are consistent with this study. The updated flows presented in this report can be used to revise flood insurance rate maps to help inform residents on flood risk impacts, which is important for the protection of life and property.

1.0 Background and Purpose

In 1968, Congress passed the National Flood Insurance Act to correct some of the shortcomings of the traditional flood control and flood relief programs. The NFIP was created to:

- Transfer the costs of private property flood losses to the property owners through flood insurance premiums.
- Provide property owners with financial assistance after floods that do not warrant federal disaster aid.
- Guide development away from flood hazard areas.
- Require that new construction be built in ways that would minimize or prevent damage during a flood.

The NFIP program is administered by the FEMA within the Department of Homeland Security. The NFIP is charged with determination of the 1% annual chance flood risk and with mapping that flood risk on the Flood Insurance Rate Maps (FIRMs). FEMA Region VI has an inventory of hundreds of thousands of river miles that are in need of flood risk mapping updates or validation. FEMA has generally maintained the FIRMs at a community and county level, but recently shifted (2010) to analyzing flood analysis at a watershed level. This transition to watershed based analysis requires a broader flood risk assessment than has historically been undertaken. Early in 2015, the Water Resources Branch of the USACE Fort Worth District began talking with FEMA Region VI representatives on ways that USACE's new basin-wide models could be leveraged in FEMA's flood risk mapping program.

In 2013, USACE established a program, known as Corps Water Management System (CWMS), to develop a comprehensive suite of models for every basin across the United States which contains a USACE asset. This modeling represents in excess of a $125 million dollar investment and provides the tools necessary to perform flood risk assessments at a larger watershed scale. Representatives of FEMA Region VI attended the CWMS implementation handoff meeting for the Guadalupe River and other basins. Subsequent discussions resulted in an interagency partnership between FEMA Region VI and USACE to produce basin-wide hydrology from these models for FEMA flood risk mapping. Additionally, USACE, the NWS and the USGS have conducted numerous hydrologic studies across Region VI, at the watershed and local scales, which can be leveraged for watershed scale flood risk assessments.

The objective of this interagency flood risk program is to establish consistent flood risk hydrology estimates across large river basins. These watershed assessments will examine the hydrology across the entire basin, reviewing non-stationary influences such as regulation and land use changes, to ensure all variables affecting flood risk in the watersheds are considered. The scope would include a multi-layered analysis with the purpose of producing flood frequency discharges that are consistent and defendable across a given basin. The multi-layered analysis will employ a range of hydrologic methods (e.g. numerical modeling, statistical hydrology, etc.) to examine all available data affecting the hydrologic processes within the watersheds. The end product of these basin-wide hydrology studies will be a hydrology report for use as a reference to evaluate against existing studies and also to support new local studies. These watershed hydrology assessments will also provide a tool set for use on local studies to provide the additional detail necessary to develop frequency flows at a smaller scale.

The basin-wide hydrology study for the Guadalupe River Basin is being conducted for FEMA Region VI by the InFRM team which includes representatives from USACE, USGS, and NWS. The scope of this basin-wide hydrology study includes a multi-layered analysis with the purpose of producing flood frequency estimates that are consistent and defendable across the basin.

This report summarizes the hydrologic analyses that were completed to estimate frequency peak stream flows for various reaches in the San Marcos River Basin. The analyses presented herein represent a portion of the work from the overall Guadalupe River Basin hydrology study that is being conducted for FEMA Region VI. The results of both statistical and rainfall runoff modeling analyses, and the draft recommended frequency discharges are summarized herein. These flow frequency estimates for the San Marcos River Basin are considered draft because the overall Guadalupe River Basin hydrology study is still ongoing.

2.0 San Marcos River Basin

2.1. Watershed and River System Description

The San Marcos River Basin is located in south Texas, approximately 30 miles northeast of San Antonio. The basin includes approximately 1,359 square miles above its confluence with the Guadalupe River near Gonzales, Texas. Significant tributaries to the San Marcos River Basin include the Blanco River and Plum Creek. The basin intersects Kendall, Blanco, Hays, Comal, Travis, Caldwell, Guadalupe, and Gonzales counties. The watershed is approximately 85 miles long and 17 miles wide and flows from west to southeast. Figure 2.1 shows the location of the San Marcos River Basin relative to the overall Guadalupe River Basin, and Figure 2.2 shows the San Marcos River Basin with its major tributaries and stream gages.

The city of Wimberley, Texas is located in Hays County at the confluence of the Blanco River with Cypress Creek. The Blanco River, which has a drainage area of 355 square miles at Wimberley, is the primary source of flooding through Wimberley. Upstream of Wimberley, the Blanco River flows through narrow canyons that 200 feet deep, following a steep stream bed over frequent outcroppings of rock. Flash flooding is a frequent problem in Wimberley, as the steep topography produces rapidly rising river stages during storm periods, leaving residents with little warning time.

The city of San Marcos, Texas is located at the confluence of the Blanco River with the San Marcos River. At San Marcos, the Blanco River has a drainage area of 436 square miles, while the drainage area of the San Marcos River is only 50 square miles. The San Marcos River above San Marcos is a spring fed stream that is largely controlled by NRCS flood detention structures. The Blanco River, on the other hand, flows through narrow canyons and steep stream beds until it approaches the San Marcos city limits. Near San Marcos, the valley widens and the stream bed flattens. Rapidly rising floodwaters from the Blanco River spread out when they reach San Marcos, inundating neighborhoods on flat floodplains and over the eastern and western drainage divides into the neighboring watersheds. The combination of the steep terrain and rapid flash flooding upstream of the city, and the flat terrain through the city itself causes substantial flood damage in San Marcos when the Blanco River exceeds its flood stage.

Below San Marcos, the San Marcos River transitions to an area of broader plains, allowing flood waters to spread out and attenuate. The downstream portions of the San Marcos River Basin, including Plum Creek, are primarily rural, with farming and ranching being the principal land uses. Luling, Texas sits on a high bluff near the confluence of the San Marcos River with Plum Creek and is less susceptible to flooding due to its elevation.

The climate over the San Marcos River Basin is generally mild. In summers, the days are hot and the nights cool. Normally, the winter periods are short and comparatively mild, but occasional cold periods of short duration result from the rapid movement of cold, high pressure air masses from northwestern polar areas and the continental western highlands. Freezing temperatures occur yearly over a large portion of the headwater area, and snowfall is experienced occasionally. Wind movements during December, January, and February are usually northerly and are influenced by continental high pressure areas. During the remainder of the year, southerly or southeasterly winds from the Gulf of Mexico are dominant. The mean annual temperature over the basin is about 68 degrees Fahrenheit. January, is the coldest month with an average minimum daily temperature of 42 degrees; August is the warmest month with an average maximum daily temperature of 94 degrees. The mean annual precipitation over the San Marcos River Basin is about 30 inches.

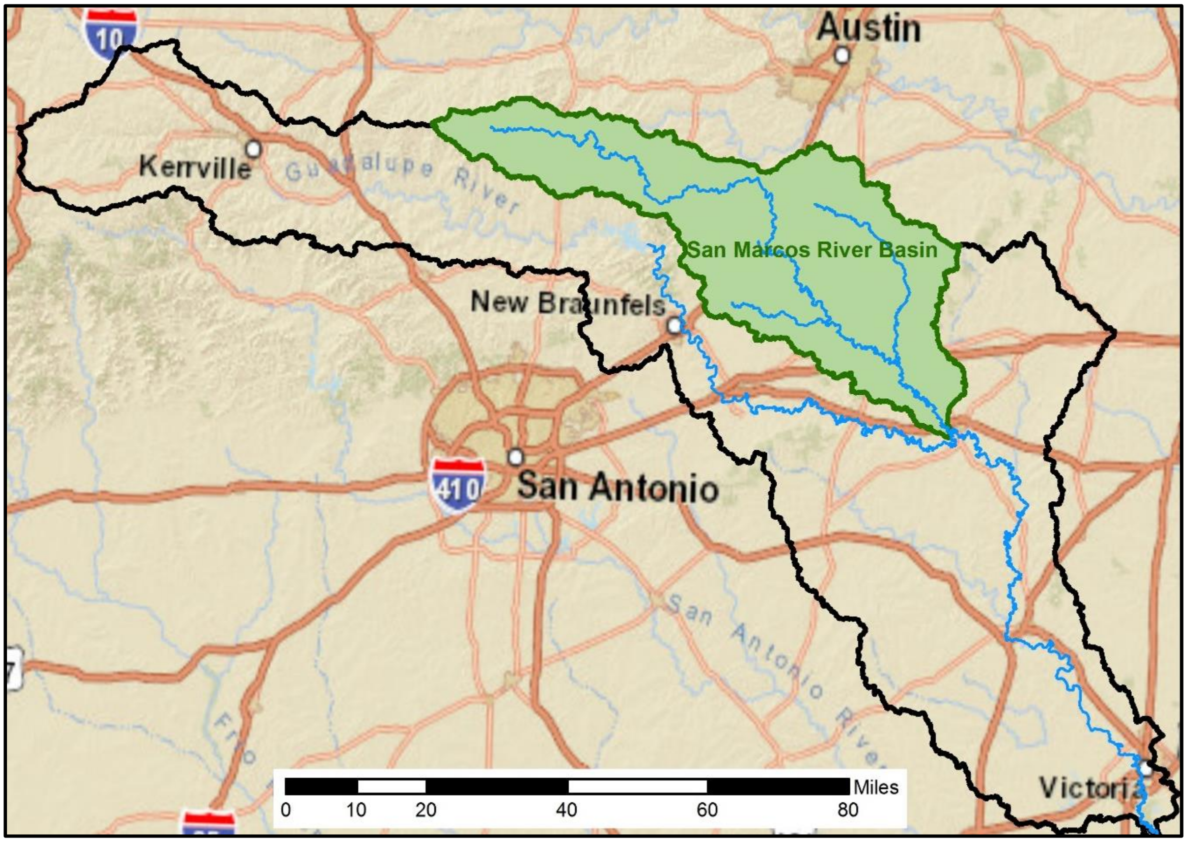

Figure 2.1: Location of the San Marcos River Basin

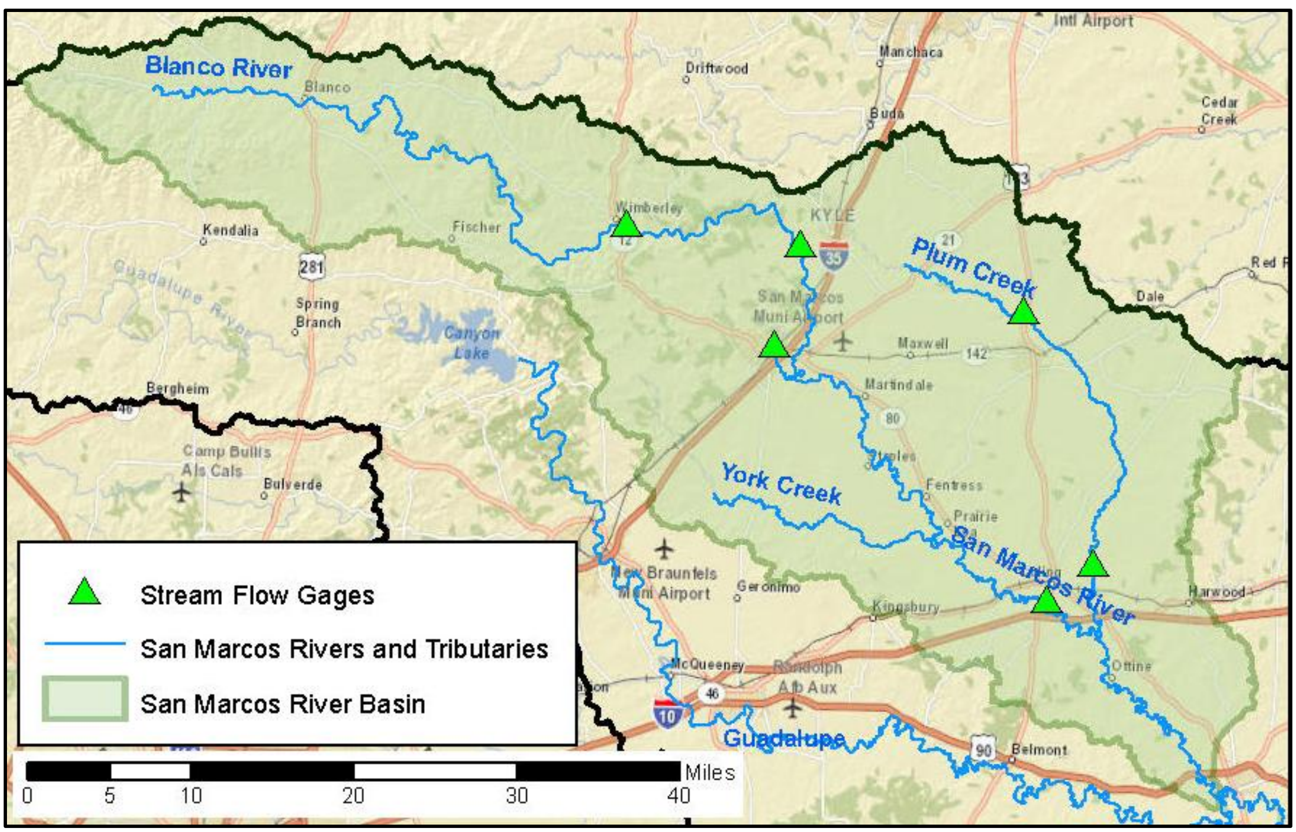

Figure 2.2: San Marcos River Basin Major Tributaries and Stream Gages

2.2. Major Floods in the Basin

The steep gradients of the streams, the thin layer of topsoil with frequent outcroppings of rock, and the narrow valleys in the Blanco River Watershed produce rapid runoff and sharp crested floods of short duration during storm periods. The river can rise as much as 40 feet in a few hours, leaving residents with little warning time. The narrow valleys and steep streams continue through the city of Wimberley itself, causing extremely high velocities through the city. Rapid variations in the flow, ranging from a few cubic feet per second (cfs) to over a hundred thousand cfs, have been experienced in the vicinity of the cities of Wimberley and San Marcos due to flooding from the Blanco River.

Recently, back-to-back large flood events occurred in the Blanco River Basin in May and October of 2015. In May 2015, heavy rainfalls produced devastating floods throughout the state of Texas. The Blanco River experienced some of the most severe flooding as a result of an intense rain event that occurred during the evenings of May 23 and 24. During that flash flood event, the Blanco River rose more than 20 feet in one hour and peaked at a stage of almost 45 feet. The flood uprooted thousands of large cypress trees, destroyed bridges and damaged or destroyed over 350 homes, some of which were washed completely off of their foundations and carried down river. The flood also resulted in 12 deaths, including two children. Property damage in the city of Wimberley was estimated at more than $30 million.

During that event, both the Kyle and Wimberley USGS stream gages on the Blanco River were damaged and ceased to operate. The May 2015 event was estimated to be the highest flood of record for the Blanco River gages at Wimberley and near Kyle. The May 2015 peak streamflow at Wimberley has been estimated by the USGS as 175,000 cfs with a peak stage of 44.90 feet. The peak for Blanco Kyle was also estimated by the USGS as 180,000 cfs. Many of the homes that were damaged in this flood event were outside of the existing FEMA 1% floodplain, and some of the high water marks that were collected after the flood were five to 10 feet higher than the existing base flood elevations (BFEs).

A second major flood occurred in October 2015. The estimated peak flows for that event were 71,000 cfs at Wimberley and 115,000 cfs near Kyle. Extensive property damage occurred once again in both Wimberley and San Marcos, with over 1,000 structures flooded in the city of San Marcos.

Other major floods that have occurred on the Blanco and San Marcos Rivers, along with their peak flow estimates, are listed in Table 2.1. Several of these floods were used as calibration events in this study's rainfall-runoff model, as denoted in the table. From this table one may observe that prior to 1998, several decades passed without a major flood event. Since 1998, there have been several major flood events that have equaled or exceeded historic flooding within the basin.

Table 2.1: Major Floods in the San Marcos River Basin

Date of Flood	Event used for Model Calibration	Observed Peak Flow (cfs)		
		Blanco River at Wimberley	Blanco River near Kyle	San Marcos River at Luling
1869		25 ft	-	40.4 ft
May-1929		113,000	139,000	37.1 ft
Sep-1952		95,000	115,000	57,000
May-1958		96,400	98,000	41,400
Oct-1998	Yes	88,500	105,000	206,000
Nov-2001	Yes	108,000	87,300	43,700
Nov-2004	Yes	34,000	31,600	84,800
Mar-2007	Yes	36,900	34,500	25,900
Jan-2012	Yes	-	-	34,700
Oct-2013	Yes	75,800	101,000	48,200
May-2015	Yes	175,000	180,000	74,800
Oct-2015	Yes	71,000	115,000	71,000

2.3. Previous Hydrology Studies

The hydrology of the Blanco and San Marcos Rivers has been analyzed many times over the years. Data and models from several existing hydrologic and hydraulic studies were available at the time of this study. Table 2.2 below summarizes all of the existing studies, models, and hydrologic information that were previously performed in the San Marcos River basin.

Table 2.2: Previous Hydrologic Studies in the San Marcos Basin

Study Name	River Extents	Frequency Flows	Hydrologic Methods	Description
Hays County Draft Flood Insurance Study by USACE 1988	Blanco and San Marcos Rivers	Yes	Rainfall-runoff modeling	NUDALLAS / HEC-1 with small subbasins, detailed HEC-2 models for routing
Hays County Effective Flood Insurance Study 1996 and 2005	Blanco and San Marcos Rivers in Hays County	Yes	USGS Regression Equations	Simple method to calculate flows with little information
Guadalupe County Flood Insurance Study 1998	San Marcos River at Luling	Yes	Statistical analysis	Statistical analysis of the San Marcos at Luling gage
USACE Lower Guadalupe Feasibility Study 2013	Entire San Marcos Basin	Yes	Rainfall-runoff modeling & Statistical analysis	HEC-HMS with large subbasins, detailed HEC-RAS models for routing, Statistical analysis of the gages
Guadalupe CWMS Implementation 2014	Entire San Marcos Basin	No	Rainfall-runoff modeling	HEC-HMS with large subbasins, calibrated to multiple flood events

2.4. Currently Effective FEMA Flows

The frequency flows that are on the currently effective flood insurance rate maps in Hays County (FEMA, 2005), which includes the cities of Wimberley and San Marcos and a large portion of the Blanco and San Marcos River Basins, were based on regression equations that were published in a USGS report in 1995 (Slade, 1995). A regression equation is a method that allows one to calculate the 1% annual chance (100-yr) flow with very little information about the watershed. In the case of the Hays County, one can simply plug two variables (the slope of the river and area of the watershed) into an equation to calculate the 1% annual chance (100-yr) flow. However, this method has its drawbacks.

The equation for the 1% annual chance (100-yr) flow was developed by drawing a “best fit” curve through the 100-yr flow points that were estimated at a number of sites across the region. The accuracy of that equation depends on many factors including the accuracy of the estimated 100-yr flow points. For Hays County, the 100-yr flow points were estimated based on a statistical analysis of the stream gage records through the year 1992. However, as documented in Table 2.1, several major floods have occurred in the San Marcos basin since 1998 which drastically change the statistical estimates of the 1% annual chance (100-yr) flow. For example, at Wimberley, in the eighteen years since 1998, there have been five major floods that have exceeded 70,000 cfs in magnitude; whereas the seventy year period prior to 1998 saw only three floods greater than 70,000 cfs, as illustrated in Figure 2.3. From the five major floods that have occurred in the last 18 years, it appears that the statistical analyses that were performed in the 1995 study significantly underestimated the 1% annual chance (100-yr) flow values.

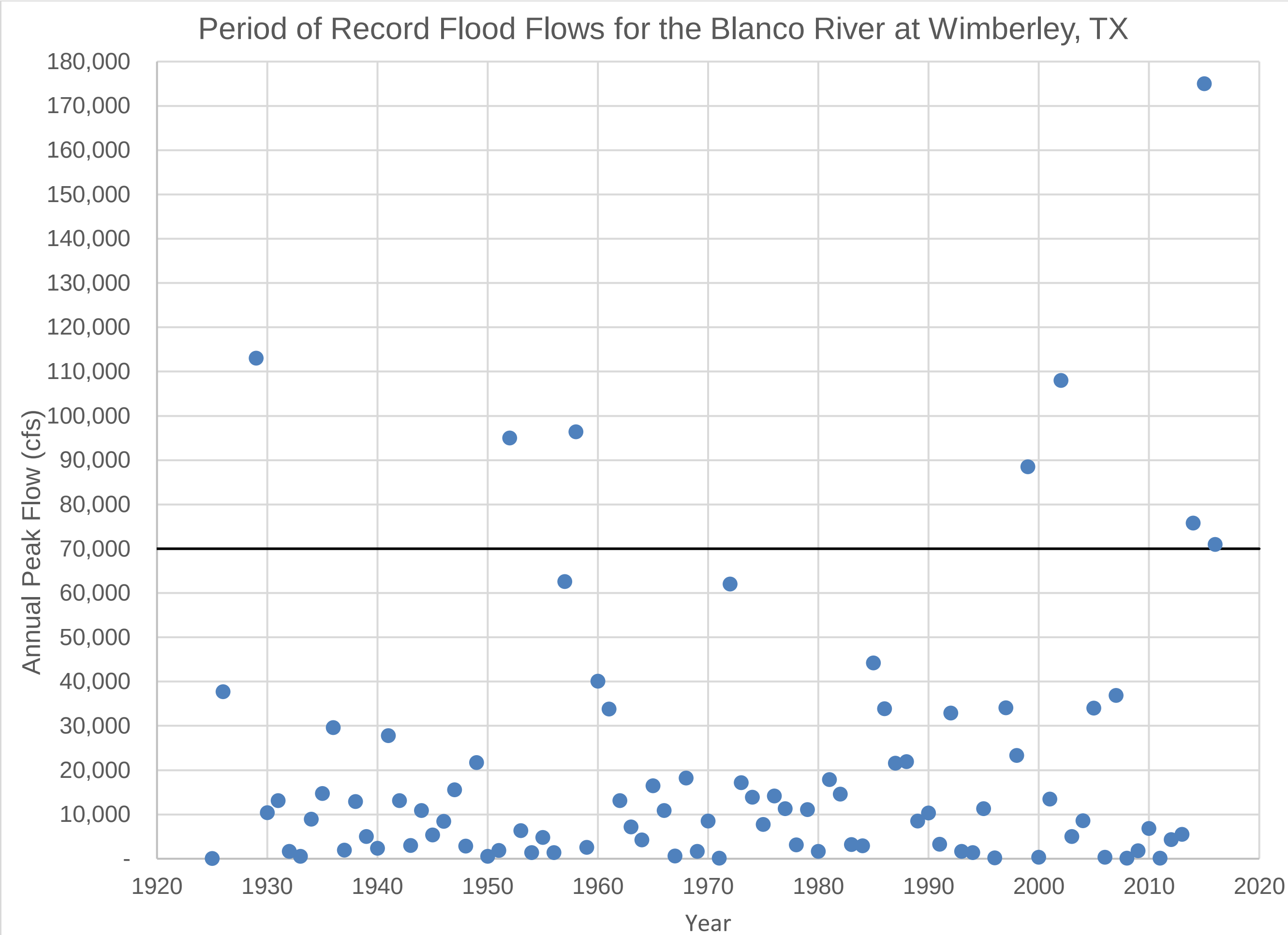

Figure 2.3: Period of Record Peak Discharges for the Blanco River at Wimberley

3.0 Methodology

The methodology that was used for this basin-wide hydrology was a multi-layered analysis that calculated frequency flows in the San Marcos River Basin through several different methods and compared their results before making final flow recommendations. The purpose of this analysis is to produce a set of frequency flows that are consistent and defendable across the basin.

The current study builds upon the information that was available from the previous hydrology studies by combining detailed data from different models, updating land use data, calibrating the models to multiple recent flood events, and updating statistical analyses to include the most recent flood events.

The multi-layered analysis for the current study of the basin consists of two main components: (1) statistical analysis of the stream gages and (2) rainfall-runoff watershed modeling in the Hydraulic Engineering Center's Hydrologic Modeling System (HEC-HMS). After completing these two different types of analyses, their results were then compared to each other and to the existing published frequency flows within the basin. Draft frequency flow recommendations were then made after consideration of all the known hydrologic information.

4.0 Data Collection

This section describes the data that was collected/reviewed for the hydrologic study effort, including geospatial and climatic information, field observations and previous reports for the San Marcos River Basin.

4.1. Spatial Tools and Reference

ArcGIS version10.2 (developed by ESRI), together with HEC-GeoHMS version 10.2 were used to process and analyze the data necessary for hydrologic modeling and to generate the sub-basin boundaries.

The geographic projection parameters used for this study are listed below:

- Horizontal Datum: North American Datum 1983 (NAD83);
- Projection: USA Contiguous Albers Equal Area Conic USGS version;
- Vertical Datum: North American Vertical Datum, 1988 (NAVD 88); and
- Linear units: U.S. feet.

4.2. Digital Elevation Model (DEM)

As part of the Guadalupe CWMS implementation, 10-meter and 30-meter DEMs were collected from the seamless USGS National Elevation Dataset (NED, accessed January 2013) for the study watershed from the http://seamless.usgs.gov <http://seamless.usgs.gov> website. The elevations of the NED are in meters. The vertical elevation units were converted from meters to feet, and the datasets were projected into the standard map projection.

In addition, high resolution LiDAR data was available for most of the basin, including Hays, Caldwell, Comal, Fayette, Guadalupe, and Gonzales counties. This LiDAR data was collected in the form of a basin wide terrain dataset created by Halff & Associates for USACE's Lower Guadalupe Feasibility Study in 2012 (Halff, Mar 2014). The final terrain dataset utilized the best available LiDAR data from various sources with collection dates varying from 2008 to 2012. The final terrain dataset was in State Plane Texas South Central 4204 projection, North American Datum (NAD) 1983 horizontal datum, and with elevations in North American Vertical Datum (NAVD) 1988. This terrain dataset was further processed into 3-foot by 3-foot DEMs for hydraulic modeling and hydrologic routing.

4.3. Vector and Raster Geospatial Data

The mapping team member utilized web mapping services and downloaded the USGS hydrologic unit boundaries, USGS stream gages, USGS medium resolution National Hydrography Dataset (NHD), National Inventory of Dams (NID) data, National Levee Database (NLD) levee centerlines as well as general base map layers. Additional vector data were obtained from the ESRI database and used in figures prepared for the final report. Raster Data includes the National Land Cover Database (NLCD) 2011 land cover layer and percent imperviousness layer from the http://seamless.usgs.gov website, accessed February 2014.

4.4. Aerial Images

The CWMS team utilized current high resolution imagery from the National Aerial Imagery Program (NAIP) with a horizontal accuracy based upon National Map Accuracy Standards (NMAS), with 1"=200' scale (1-foot imagery) accuracy of +/- 5.0-feet and the 1"=100' scale (0.5-foot imagery) accuracy of +/- 2.5-feet. Digital photos were used to verify watershed boundaries as well as delineate centerlines and other geographic features. In addition, Google Earth, and Bing Maps were also used to locate important geographic features.

4.5. Soil Data

Gridded Soil Survey Geographic (SSURGO) datasets were obtained during the Guadalupe CWMS study. These datasets were used to estimate initial and constant loss rates for the frequency storm events in HEC-HMS and to calculate initial estimates of the Snyder's lag time. The lag times were modified during calibration.

4.6. Precipitation Data

Historic precipitation data for observed storm events were collected from the NWS gridded precipitation data files. NEXRAD Stage III grids were used for the basin. The NEXRAD Stage III grids are stored in a binary file format called XMRG. The historical XMRG data were processed into hourly precipitation grids in HEC-DSS format using HEC-METVUE. This data was acquired from the NWS West Gulf River Forecasting Center (WGRFC) and the http://dipper.nws.noaa.gov/hdsb/data/nexrad/nexrad.html website.

Frequency point rainfall depths of various durations and recurrence intervals were collected for the Blanco and San Marcos River Basins from the 2004 Atlas of Depth-Duration Frequency (DDF) of precipitation for Texas published by the USGS (Asquith, 2004). The point rainfall depths for the Blanco River subbasins were taken from a point near Wimberley, Texas, as shown in Table 4.1. The point rainfall depths for the rest of the San Marcos subbasins were taken from a point near the lower basin's centroid, as shown in Table 4.2. These also happened to be the same point rainfall depths as were used in the Lower Guadalupe feasibility study. Both sets of frequency precipitation depths were utilized in the final HEC-HMS rainfall-runoff model.

Table 4.1: Frequency Point Rainfall Depths (inches) for the Blanco River Basin

Duration	Recurrence Interval							
	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	250-yr	500-yr
15min	1.00	1.24	1.41	1.75	2.00	2.25	2.65	2.95
1hr	1.74	2.30	2.70	3.25	3.80	4.33	5.20	5.90
2hr	2.20	2.90	3.42	4.10	4.80	5.60	6.60	7.60
3hr	2.40	3.18	3.75	4.55	5.30	6.20	7.40	8.60
6hr	2.73	3.67	4.27	5.20	6.10	7.10	8.60	10.00
12hr	3.08	4.10	4.90	6.00	7.00	8.20	10.00	11.90
24hr	3.70	5.10	6.18	7.60	8.80	10.10	12.10	14.00

Table 4.2: Frequency Point Rainfall Depths (inches) for the San Marcos River Basin

Duration	Recurrence Interval							
	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	250-yr	500-yr
15min	1.07	1.41	1.66	2.02	2.33	2.69	3.23	3.71
1hr	1.83	2.41	2.82	3.41	3.9	4.45	5.29	6.01
2hr	2.3	3.07	3.61	4.39	5.06	5.8	6.94	7.93
3hr	2.41	3.29	3.94	4.87	5.68	6.59	8	9.25
6hr	2.73	3.68	4.38	5.39	6.27	7.27	8.82	10.2
12hr	3.14	4.26	5.08	6.27	7.31	8.49	10.32	11.95
24hr	3.6	5.1	6.18	7.67	8.9	10.23	12.15	13.75

4.7. Stream Flow Data

The USGS stream flow gages located in the basin are listed in Table 4.3 below. Table 4.3 also indicated whether the gage record was used in this study's statistical analysis or in the calibration of the HEC-HMS model. For these gage sites, annual peak flow data and 15-minute stream flow and stage data was collected from the USGS NWIS website. The locations of these stream gages are shown by their SHEF IDs in the basin map on Figure 4.1.

Table 4.3: USGS Stream Flow Gages in the San Marcos Basin

SHEF ID	USGS ID	Location Description	Gage Type	Drainage Area (sq mi)	Used in HEC-HMS Calibration	Included in the Statistical Analysis
WMBT2	08171000	Blanco River at Wimberley, TX	Flow/stage	355	Yes	Yes
KYET2	08171300	Blanco River nr Kyle, TX	Flow/stage	412	Yes	Yes
SRUT2	08170500	San Marcos at San Marcos, TX	Flow/stage	49	Yes	Yes
SMMT2	08171400	San Marcos Rv nr Martindale, TX	Stage	547	No	No
LLGT2	08172000	San Marcos River at Luling	Flow/stage	838	Yes	Yes
LCPT2	08172400	Plum Creek at Lockhart	Flow/stage	112	Yes	Yes
LULT2	08173000	Plum Creek nr Luling	Flow/stage	309	Yes	Yes

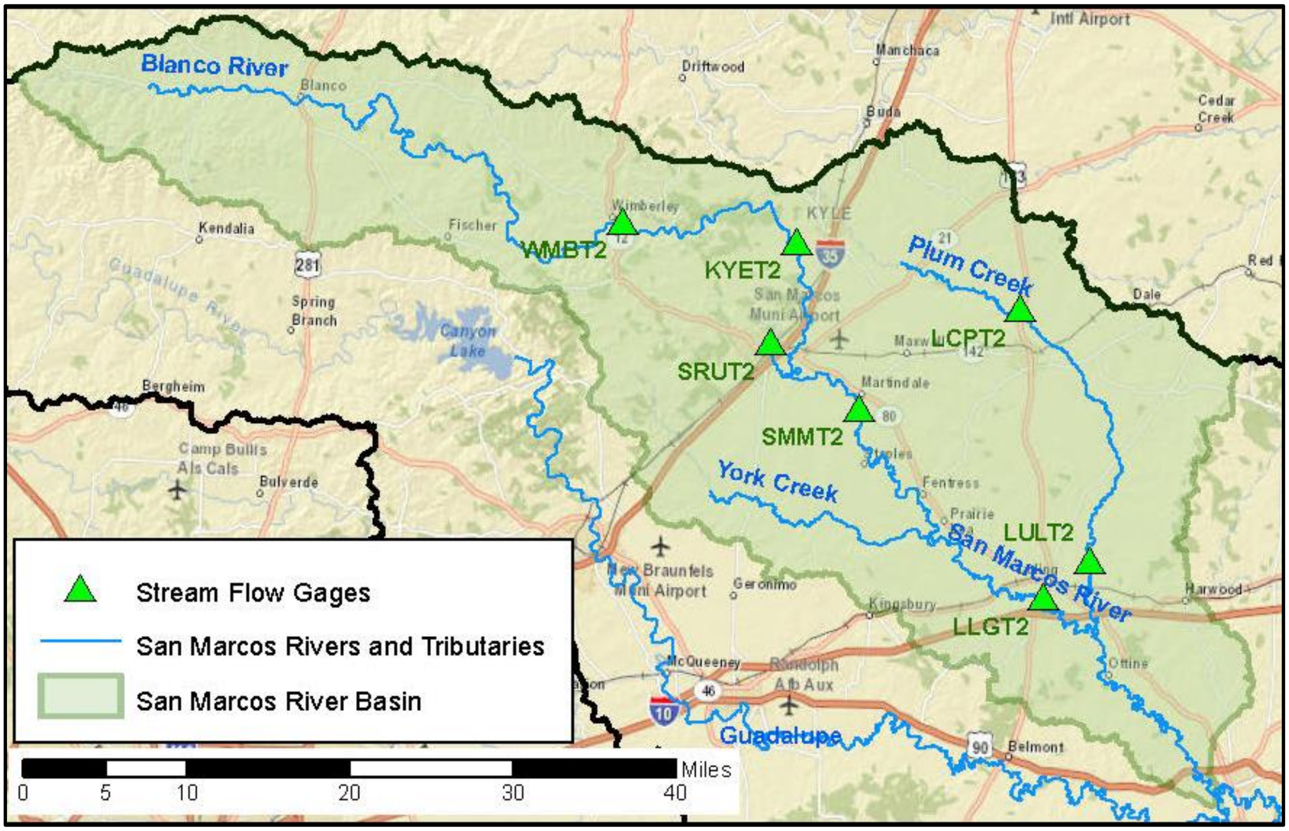

Figure 4.1: Stream Flow Gage Locations

4.8. Reservoir Physical Data

A total of 94 NRCS dams and other small dams are located within the basin. Of these, reservoir elements were used in the HEC-HMS rainfall-runoff model for four NRCS dams in the upper San Marcos basin. These dams were selected to be modeled in detail due to their sizable flood storage and their proximity to developed areas. Table 4.4 summarizes the reservoir data obtained for these dams and their corresponding data sources. An additional 90 NRCS and other small dams were scattered throughout the rural areas of the basin, especially on the York Creek and Plum Creek watersheds. These dams were not modeled in detail but were accounted for in the model through adjustments to the loss rates and peaking coefficients. Data for these dams was obtained from the National Inventory of Dams (USACE, 2016).

Table 4.4: Reservoir Data and Sources for Dams Modeled in Detail

Reservoir / Facility	Data	Source(s)
Upper San Marcos NRCS Site 1	Elevation-Storage, Spillway and Outlet Structures	NRCS As-Built Plans
Upper San Marcos NRCS Site 2	Elevation-Storage, Spillway and Outlet Structures	NRCS As-Built Plans
Upper San Marcos NRCS Site 3	Elevation-Storage, Spillway and Outlet Structures	NRCS As-Built Plans
Upper San Marcos NRCS Site 5	Elevation-Storage-Discharge	NRCS As-Built Plans

4.9. Software and Documentation

The following table provides a summary of the significant computer software programs and versions that were used in the hydrologic analysis of the basin.

Table 4.5: List of Computer Programs Used in this Hydrology Study

Program	Version	Capability	Developer
ArcGIS	10.2	Geographical Information System	ESRI
HEC-DSSVue	2.0.1	Plot, tabulate, edit and manipulate data in HEC-DSS format	HEC
HEC-GeoHMS	10	Watershed delineation and generating HEC-HMS input	HEC
HEC-METVUE	2.2.10.2 Beta	Processing and viewing precipitation data	HEC
HEC-HMS	4.1	Rainfall-runoff simulation	HEC
HEC-RAS	4.1	Steady and Unsteady Flow Analysis, ModPuls routing	HEC
PeakFQ	7.1	Statistical Analysis of Gage Records for Flood Frequency	USGS

5.0 Statistical Hydrology

Statistical analysis of the observational record (systematic and historical) at USGS streamflow-gaging stations provides an informative means of estimating flood frequency flows. The annual peak streamflow data as part of systematic operation of a streamflow-gaging station provide the foundation, but additional historical information or anticipated flow contexts also can be used. An annual peak streamflow is defined as the maximum instantaneous streamflow for a streamflow-gaging station for a given water year, and annual peak streamflow data for USGS streamflow-gaging stations can be acquired through the USGS National Water Information System (NWIS) (USGS, 2016). The statistical analyses are based on water year increments. A water year is the 12-month period October 1 through September 30 designated by the calendar year in which it ends.

For the statistical hydrology portion of the multi-layered analysis, InFRM team members from the USGS analyzed annual peak streamflow gage records for the USGS streamflow-gaging stations listed in Table 5.1.The locations of the USGS streamflow-gaging stations that were included in the statistical analysis are also shown on Figure 5.1. The USGS streamflow-gaging station for the San Marcos River near Martindale, though located on the river main stem, was not included because it lacks a sufficient period of record (2011 to present) to support computation of flood flow frequency.

Table 5.1: Summary of the USGS Streamflow-Gaging Stations included in the Statistical Analysis

[Est., estimated; mi², square miles; --, dimensionless or not applicable; in., inches; ft³/s, cubic feet per second; acre-ft/mi², acre-feet per square mile; PRISM, data product of the Northwest Alliance for Computational Science and Engineering (2016, accessed on July 16, 2016 at *http://www.prism.oregonstate.edu/explorer/*); MGBT-0, indicates that the Multiple Grubbs-Beck test for low-outlier threshold did not identify low outliers, unfortunately USGS-PeakFQ software does not report the numerical value of the threshold.]

Station number	Streamgage name	Latitude	Longitude	Horizontal datum as reported by NWISWeb public interface	Period of analyzed annual peak stream-flows	Contri-buting drainage area	Main-channel slope (Asquith and Roussel, 2009)	Mean annual rainfall (PRISM 1981–2010)	Cumulative flood storage for last year of analysis	Est. effect of cumulative flood storage on mean annual peak streamflow (Asquith, 2001, fig. 11a)	Low-outlier threshold used	Kendall's Tau p-value of analyzed annual peak streamflows
						(mi²)	(--)	(in.)	(acre-ft/mi²)	(ft³/s)	(ft³/s)	(--)
08170500	San Marcos River at San Marcos, Tex.	29°53'20"	97°56'02"	NAD27	1995–2015	48.9	--	33.68	520.12	-271	MGBT-0	0.315
08171000	Blanco River at Wimberley, Tex.	29°59'39"	98°05'19"	NAD27	1869–2016	355.0	0.00342	36.63	2.50	0	1,360	0.542
08171300	Blanco River near Kyle, Tex.	29°58'45"	97°54'35"	NAD27	1929–2016	412.0	0.00315	34.79	2.16	0	4,000	0.597
08172000	San Marcos River at Luling, Tex.	29°39'58"	97°39'02"	NAD27	1869–2016	838.0	0.00172	34.16	73.95	-1,362	MGBT-0	0.738
08172400	Plum Creek at Lockhart, Tex.	29°55'22"	97°40'44"	NAD27	1959–2016	112.0	0.00327	34.56	360.38	-532	1,380	0.830
08172400.01	Plum Creek at Lockhart, Tex.	29°55'22"	97°40'44"	NAD27	1930–2016	112.0	0.00327	34.56	360.38	-532	1,380	0.830
08173000	Plum Creek near Luling, Tex.	29°41'58"	97°36'12"	NAD27	1930–2016	309.0	0.00209	34.67	221.08	-1,142	5,910	0.878

There is a duplicated entry in the table for Plum Creek at Lockhart because an alternative analysis was made. The period of time analyzed for the two entries for Plum Creek at Lockhart have a different beginning year. The two columns related to "flood storage" are discussed in Section 5.6.

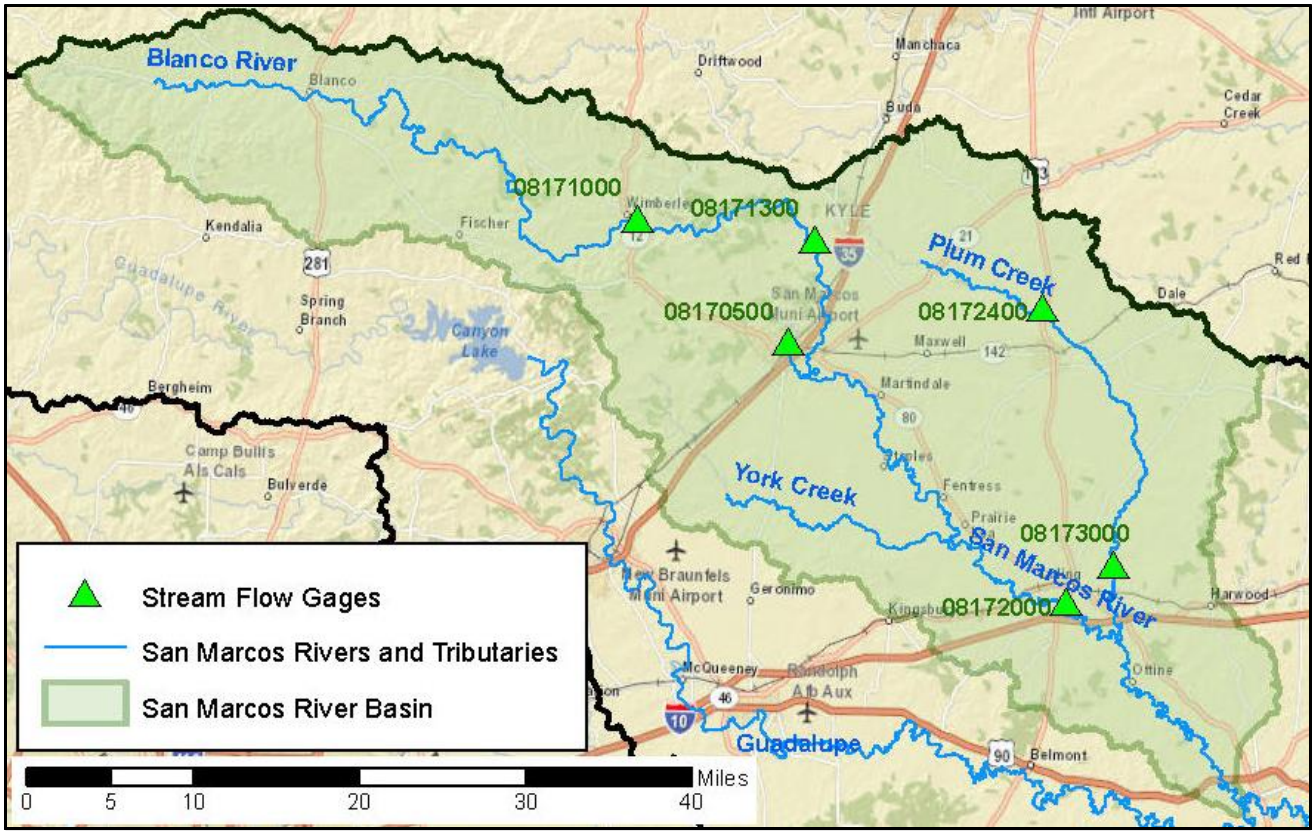

Figure 5.1: Map of USGS Streamflow-Gaging Stations included in the Statistical Analysis

5.1. Statistical Methods

The statistical methods involved in this chapter include the fitting of a log-Pearson Type III probability distribution (LPIII) to the data. The general purpose of fitting a probability distribution is to provide an objective mechanism to extrapolate to hazard levels (as represented by annual exceedance probabilities and equivalently expressed as annual recurrence interval or recurrence interval measured in years) beyond those represented by the sample size of annual peak streamflow data for a given streamflow-gaging station. A distribution, such as the LPIII, can be fit by numerous methods, and the logarithms (base-10) of the annual peak streamflow data are most commonly used in practice. The USGS-PeakFQ software version 7.1 (Veilleux and others, 2013; USGS, 2014) provides the foundation for the results of the flood frequency flows which are specified by average annual recurrence intervals computed and extracted from software output at 2, 5, 10, 25, 100, 200, and 500 years and accompanying by the 95-percent confidence limits.

Other statistical techniques used for data evaluation included the Kendall Test. The Kendall's tau test (Hollander and Wolfe, 1973; Helsel and Hirsch, 2002) was used through the USGS-PeakFQ software to detect for the presence of monotonic trends in the annual peak streamflow data. Kendall's tau test is a popular statistic for quantifying the presence of monotonic changes in the central tendency of streamflow data in time. The Kendall tau results are listed in Table 5.1, and none of the streamflow-gaging stations show a trend in annual peak streamflow at an alpha of 0.10 significance level.

Flood flow frequency analyses were conducted for the streamflow-gaging stations using the annual peak data from the USGS NWIS website (USGS, 2016) with historical information when available and data augmentation when required. The Interagency Advisory Committee on Water Data (IACWD) (1982) describes a so-called Bulletin 17B method (B17B) to conduct the frequency analysis (USGS, 2014), but the statistical frequency analysis performed for the San Marcos basin are focused on updated guidelines from so-called Bulletin 17C (England and others, 2016).

The use of the expected-moments algorithm (EMA, England and others, 2016; USGS, 2014) permits sophisticated interpretations of the historical record intended to enhance the estimates of peak streamflow, especially for the rare frequency events such as the 1% annual chance (100-yr) streamflow. Inclusion of historical record interpretations can have net impact of lowering (decreasing) flood flow frequency estimates for the largest of streamflows because the largest documented events are assigned lower empirical probabilities. EMA also permits inclusion of nonstandard information such as data censoring. For example, an annual peak might be known to be lower than a specified discharge threshold. EMA can also accommodate time varying discharge thresholds based on assigning a discharge threshold as a highest since within discrete blocks/intervals of time. This nonstandard information collectively can be thought of as a framework fostering record extension.

Although the drainage-area ratio method can be used for record extension (Asquith and others, 2006), because of the available overlapping years of annual peak streamflow in select circumstances, the line of organic correlation (LOC) described by Helsel and Hirsch (2002) and equivalently the method of total-least squares (TLS) is preferred for record extension when two stations are compared. The TLS regression is also preferred over conventional linear regression because of a critical need for variance maintenance; conventional regression will result in underestimation of variability and hence a peak streamflow frequency curve that would not be steep enough and is expected to contribute to underestimation of flood flow frequency. Application of TLS is streamflow-gaging station-specific and discussed in Section 5.2. A TLS regression equation was used to make estimates of discharge and these were converted to a discharge interval by adding and subtracting one-standard deviation of the equation from the estimate to form the interval.

Two especially important options of the USGS-PeakFQ software are the choice of low-outlier threshold and generalized skew and whether to incorporate such skew in the analyses in a weighting between the generalized skew and that computed using the site-specific data. Low outliers within a time series of peak streamflow, such as annual peaks that in reality were likely not storm flows or highly localized storm flow, often need removal from the analysis using a form of conditional probability adjustment. To this end, the so-called Multiple Grubbs-Beck low-outlier threshold (MGBT) was used. For streamflow-gaging station-specific reasons, the analyst can manually specify a low-outlier threshold. These are identified in Section 5.2 and listed in Table 5.1. Skew is an expression of the curvature or shape of the LPIII distribution intended to mimic that of the data (Asquith, 2011 a,b). The importance of a generalized or regional skew is stressed in IACWD (1982) to mitigate for high sampling variance using typical streamflow-gaging station record lengths. A substantial motivation for a generalized skew is to compensate for inefficient estimation of the product moment skew for highly variable and skewed data such as annual peak streamflow. The generalized skew coefficient is a built-in feature of USGS-PeakFQ but can be overridden by the user. Because of age as well as study objectives for the present (2016) study, the maps of generalized skew for Texas in IACWD (1982) or Judd and others (1996) are of uncertain applicability for this study. The former reference represents a highly generalized estimate of skew dating from about the late 1970s, the later reference represents a substantially more recent, but still dated, estimate of generalized skew for Texas. Low-outlier thresholds can greatly affect the estimate of skewness; for this study, the station-skew option in USGS-PeakFQ exclusively was used.

Confidence limits of flood flow frequency can be informative to decision makers. The lower and upper limits of 95-percent confidence intervals were computed for this study. Confidence intervals can be expected to encompass the true value 95 percent of the time (Good and Hardin, 2003, p. 100). The range in these numbers for the lower and upper 95-percent confidence limits increases with the more extreme events.

5.2. Stream Gage Data

San Marcos River at San Marcos, Texas

The systematic stream gage record for the San Marcos River at San Marcos is 1995 to 2015. The 1999 peak streamflow was 21,500 cubic feet per second (ft^3/s) at a stage of 21.29 feet (ft), which is the flood of record at that location. This is a problematic site to interpret owing to relatively short record length and spring flow dominated hydrologic processes with some local storm flow. The 2012 and 2015 peaks are unrecorded in USGS peak streamflow databases (USGS, 2016). The 2012 peak was inferred from unit-values as 809 ft^3/s (05/10/2012). The 2015 peak was affected by backwater from the Blanco River. A discharge interval was developed for the 2015 peak as 237 <=> 21,500 ft^3/s, where the smaller value is the daily mean streamflow for 05/24/2015 and the larger value is the 1999 peak discharge. The 1999 peak discharge quite likely is the largest of a considerable historical time span, and frequency analysis results for this station are highly influenced by the absence and (or) inclusion of how the 1999 peak is interpreted. The data as set up for statistical frequency analysis are shown in Figure 5.2, in which the discharge interval for 2015 is seen.

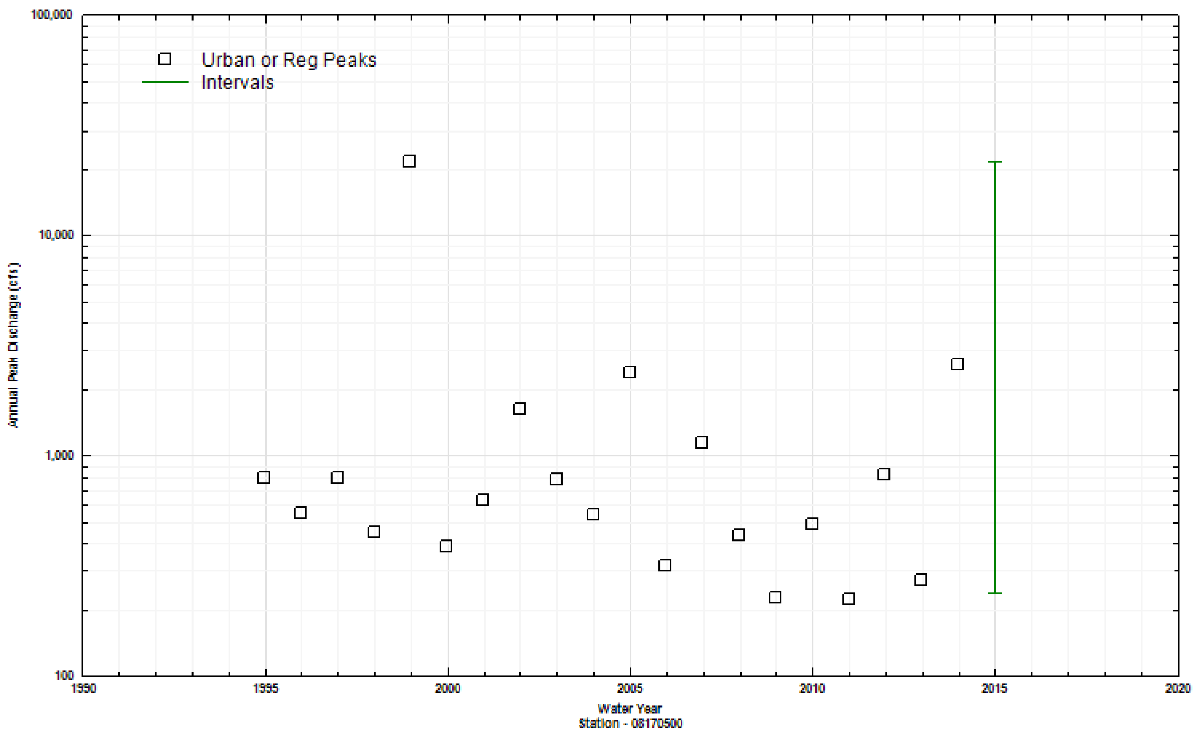

Figure 5.2: Annual Peak Streamflow Data for the San Marcos River at San Marcos, TX

Blanco River at Wimberley, Texas

The systematic record for Blanco at Wimberley is 1925 to 1926 and 1929 to 2016. The peak streamflow in 1929 of 113,000 ft3/s at a stage of 33.30 ft is believed to be the highest since 1869 and also was the highest peak until May 2015 as documented in USGS (2016) data. The peak of record occurred in May 2015 at 175,000 ft3/s and stage of 44.90 ft. The peak in late October 2015 indicates that water year 2016 annual peak will be at least 71,000 ft3/s. The joint probability of timing in the water year for some 1,475 peaks was investigated. Inclusion of the incomplete 2016 water year is deemed judicious because late October 2015 was itself a substantial event and thus inclusion of 71,000 ft3/s at this time represents at least a minimum impact on the fitted frequency curve. The data as set up for statistical frequency analysis are shown in Figure 5.3, in which the two rectangular regions demark the historical context of the 1929 peak.

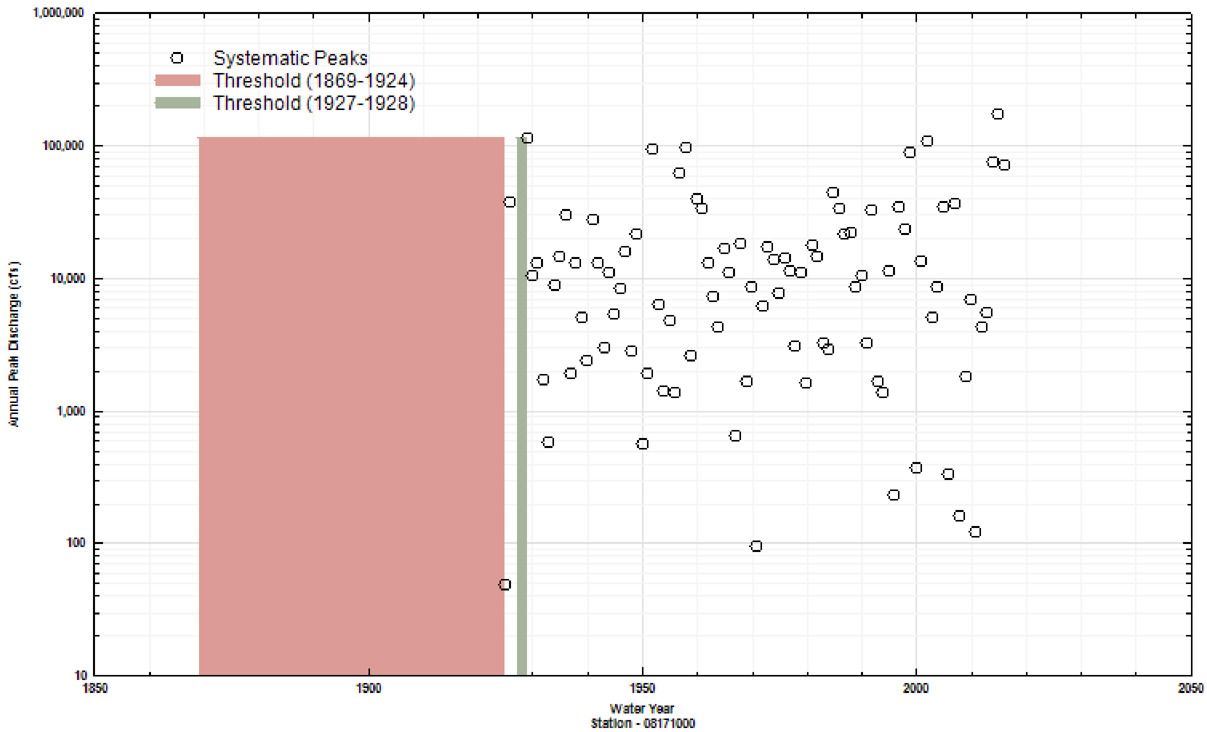

Figure 5.3: Annual Peak Streamflow Data for the Blanco River at Wimberley, TX

Blanco River near Kyle, Texas

The systematic record for the Blanco River near Kyle is 1957 to 2016 for which historical peak streamflows in 1929 (139,000 ft3/s at stage of 40.00 ft) and 1952 (115,000 ft3/s at a stage of 38.00 ft) are also available. The 1929 peak streamflow is considered the highest since 1882 as documented in USGS (2016) data. Because of proximity to Blanco Wimberley and the high degree of correlation of large annual peaks between the two streamflow-gaging stations, the 1929 peak at Blanco Kyle was assumed to be the highest since 1869 in lieu of 1882. The historical record is interpreted as 139,000 ft3/s being the highest in the period 1869 to 1928. The period of record at Kyle is not as long as Wimberley, but because physically much of the same watershed is monitored by each stream gage, additional inferences can be made through TLS regression. From TLS regression analysis between Wimberley and Kyle, a discharge threshold of 32,822 ft3/s for the period 1930 to 1951 was used, and a discharge threshold of 6,822 ft3/s for the period 1953 to 1956. A low-outlier threshold of 4,000 ft3/s was chosen for statistical frequency computations. Similar to the Wimberley streamflow-gaging station, a special addition of 2016 was made. The May 2015 peak streamflow at Kyle was estimated at 180,000 ft3/s, which is the highest flood of record at that location. The October 2015 peak of 115,000 ft3/s was incorporated into the analysis as the presumed annual peak for water year 2016. The data as set up for statistical frequency analysis are shown in Figure 5.4, in which the three rectangular regions demark the historical context corresponding to the three discharge thresholds identified.

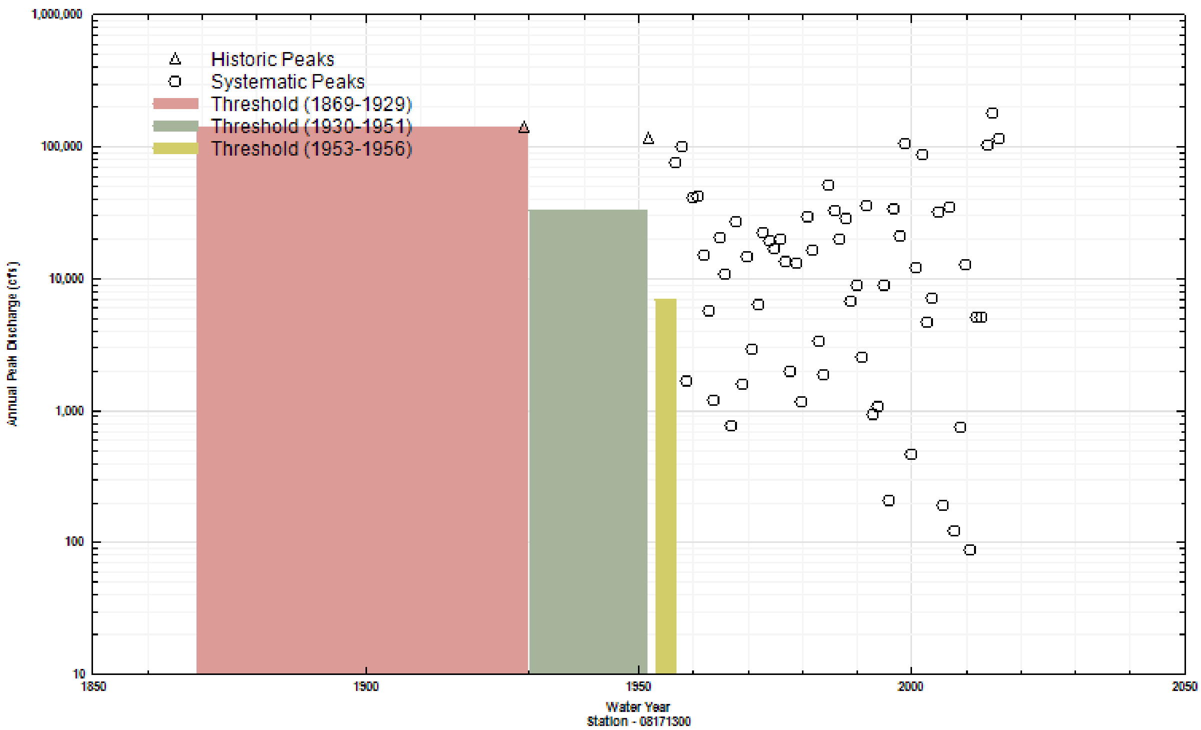

Figure 5.4: Annual Peak Streamflow Data for the Blanco River near Kyle, TX

San Marcos River at Luling, Texas

The systematic record for the San Marcos River at Luling is 1940 to 2016. Both regulated and unregulated records were accepted into the analysis for two primary reasons: (1) the regulation in the San Marcos-Luling watershed is considered passive through detention storage in small flood-water retarding structures, and (2) visualization of the time series of annual peaks does not indicate a situation in which the data should not be combined. Even in the presence of regulated streamflow record, it is clear that large magnitude peaks can occur. The October 1998 peak of 206,000 ft3/s and stage of 41.85 ft is considered the highest since 1859. From TLS regression analysis between streamgages San Marcos at Luling and Plum Creek near Luling, the period 1930 to 1939 can be found in Table 5.2. The substantial peak in late October 2015 indicates that water year 2016 annual peak will be at least 71,000 ft3/s. Special addition of incomplete water year 2016 was made where 71,000 ft3/s is the October 31, 2015 peak unit-value of discharge. The data as set up for statistical frequency analysis are shown in Figure 5.5, in which the rectangular region demarks the historical context of the October 1998 peak. The discharge intervals are represented as green bars in the figure.

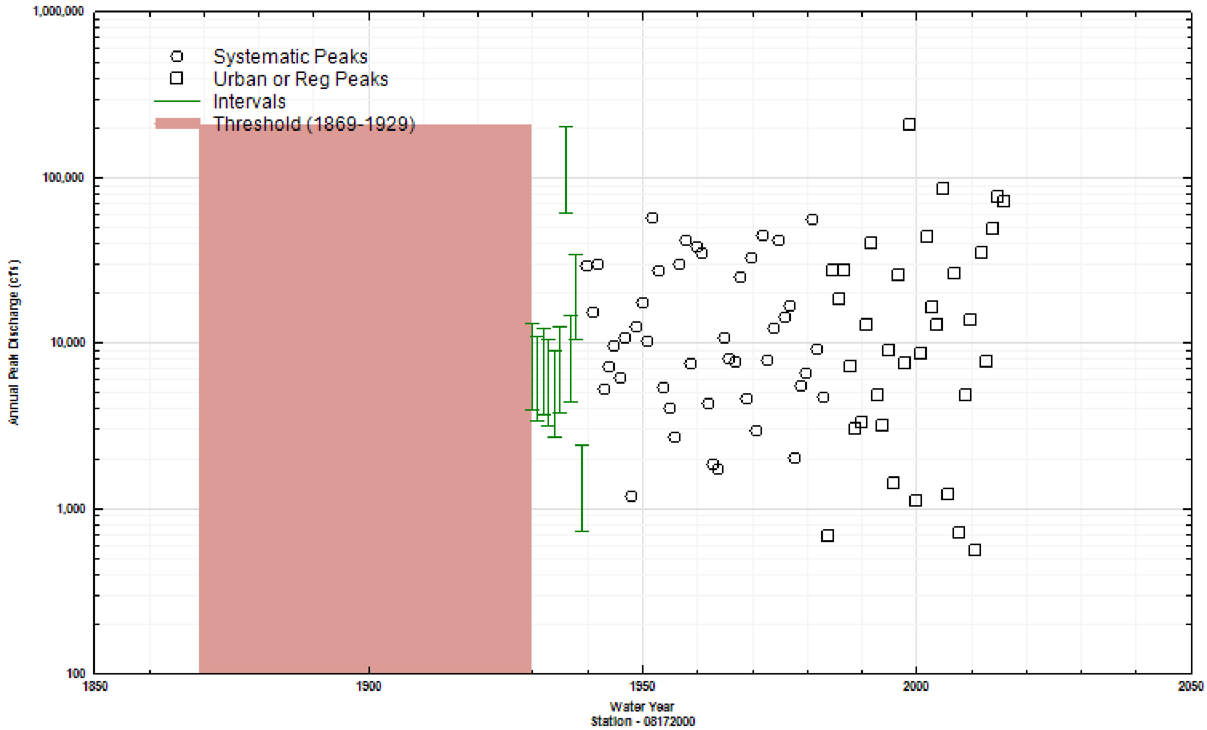

Figure 5.5: Annual Peak Streamflow Data for the San Marcos River at Luling, TX

Plum Creek at Lockhart, Texas

The systematic record for the Plum Creek at Lockhart is 1959 to 2016. Both regulated and unregulated records were accepted into the analysis. Visualization of the time series of annual peaks does not indicate a situation in which the data should not be pooled together. The October 1998 peak of 47,200 ft3/s at stage of 23.09 ft is the largest for the period of record. The substantial peak in late October 2015 indicates that water year 2016 annual peak will be at least 39,100 ft3/s from the unit values. Special addition of incomplete water year 2016 was made. The data as set up for statistical frequency analysis are shown in Figure 5.6.

An alternative scenario for Plum Creek at Lockhart was made due to a large gap in record relative to downstream streamflow-gaging station Plum Creek near Luling located on same watershed main stem. This scenario is preferable because the 1999 peak was so large and of considerable historical importance. The 1930 to 1958 information gap relative to Plum Creek near Luling was augmented by TLS regression and can be found in Table 5.2. This special scenario is identified by a pseudo-USGS station identification number 08172400.01 or 0817240001 (depending on software limitations). The data as set up for statistical frequency analysis for the alternative scenario are shown in Figure 5.7, in which the above listed discharge intervals are represented as green bars in the figure.

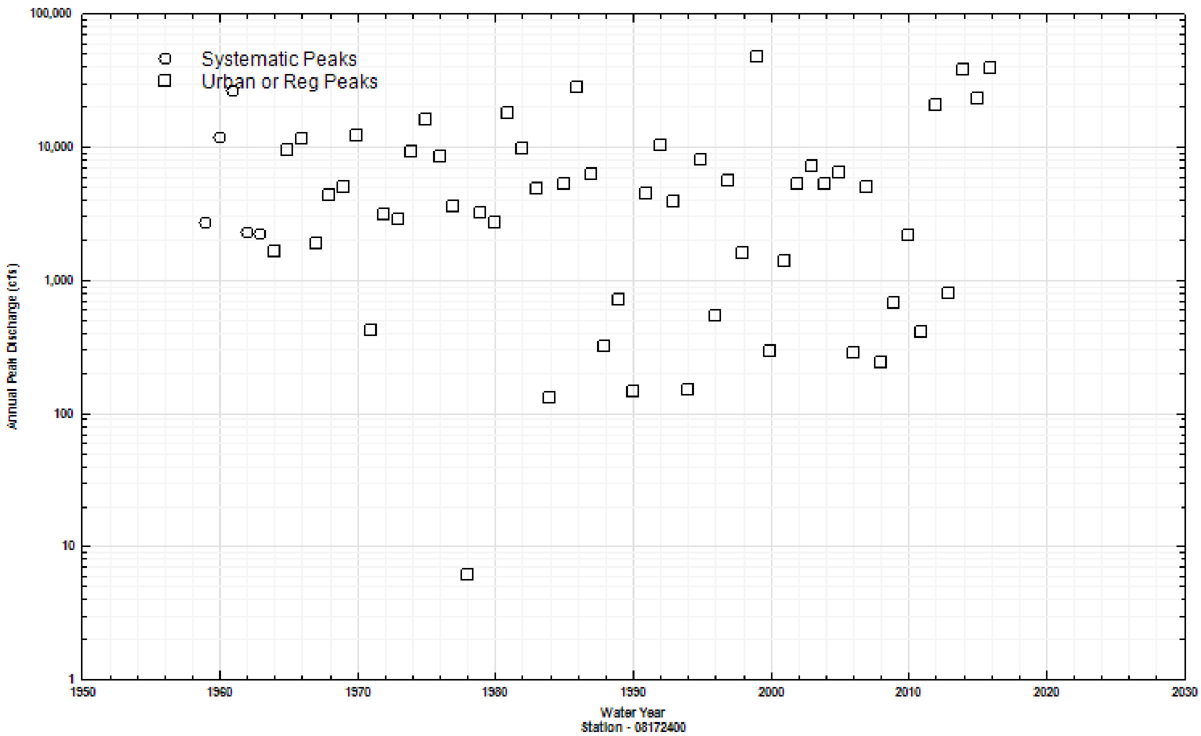

Figure 5.6: Annual Peak Streamflow Data for Plum Creek at Lockhart, TX

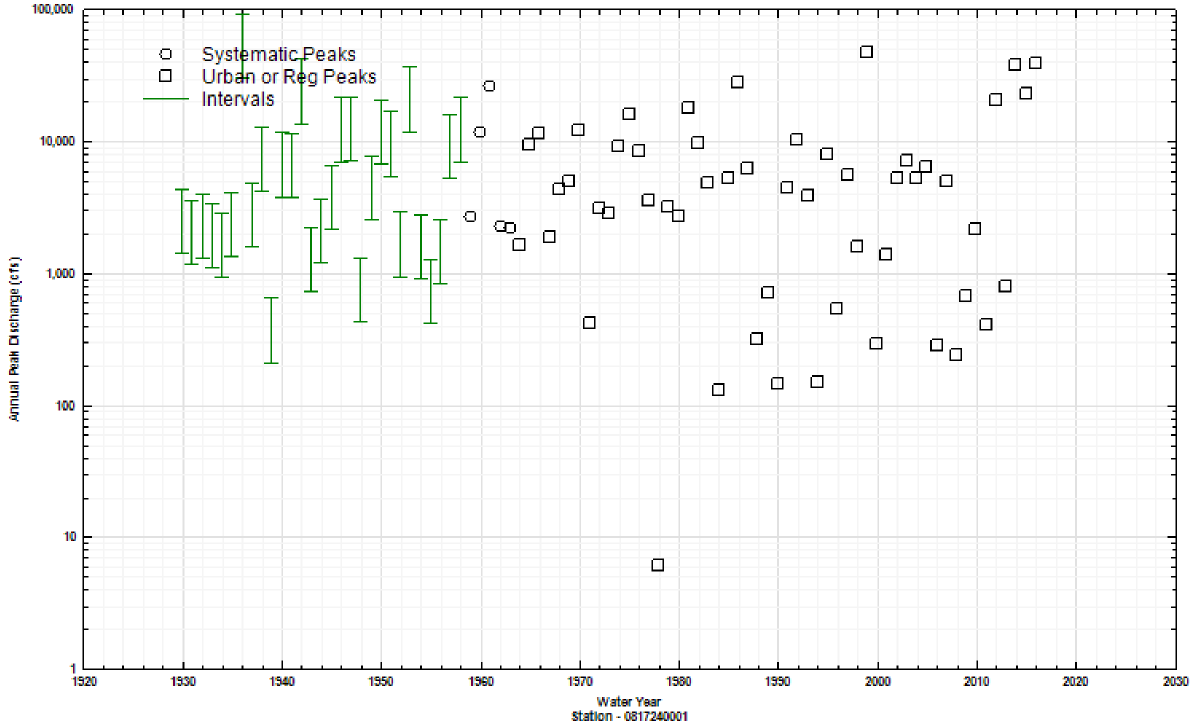

Figure 5.7: Annual Peak Streamflow Data for Plum Creek at Lockhart, TX (alternative analysis)

Plum Creek near Luling, Texas

The systematic record for Plum Creek near Luling is 1930 to 1993 and 2001 to 2016. Two scenarios were computed and subsequently combined by arithmetic averaging for reasons described as follows. Both regulated and unregulated records were accepted into the analysis because the regulation in the Plum Creek near Luling watershed is considered passive through detention storage in small flood-water retarding structures, and more importantly, visualization of the time series of annual peaks does not indicate a situation in which the data should not be pooled together. Even in the presence of regulated streamflow record, it is clear that large magnitude peaks can occur. A quite substantial peak associated with the October 2015 event occurred. Special addition of incomplete water year 2016 was made where 15,800 ft3/s is the October 31, 2015 peak unit-value of discharge.

Plum Creek near Luling was not operational from 1994 to 2000. Within this gap, it is near certain that a major event occurred in October 1998 based on other stations. Two scenarios of analysis where done with the only difference being how the gap from 1994 to 2000 is treated. In scenario 1 a TLS regression of observed data between Plum Creek near Luling and San Macros River at Luling was developed and the results can be found in Table 5.2. The data as set up for statistical frequency analysis for scenario 1 is shown in Figure 5.8 in which the discharge intervals are represented as green bars. In scenario 2, a TLS regression of observed data between Plum Creek near Luling and Plum Creek at Lockhart was used and the results can be found in Table 5.2. The data as set up for statistical frequency analysis for scenario 2 is shown in Figure 5.9, in which the discharge intervals are represented as green bars.

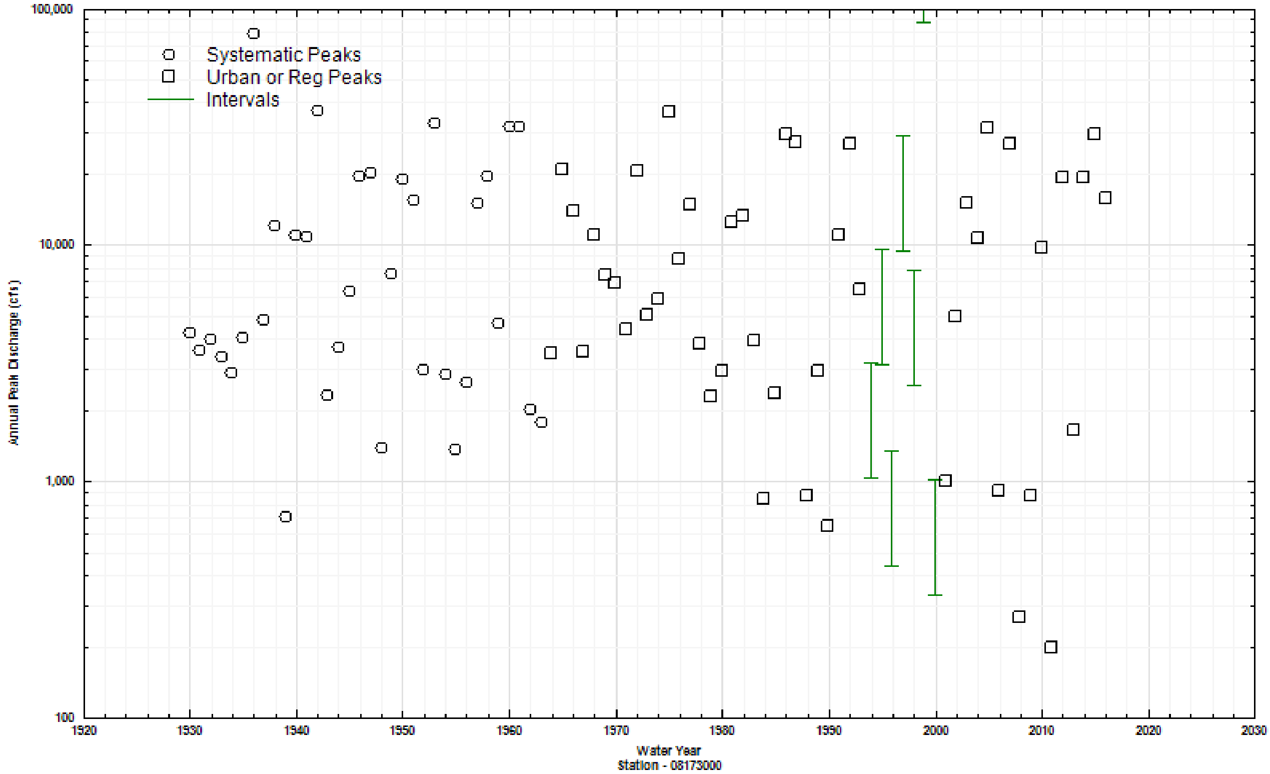

Figure 5.8: Annual Peak Streamflow Data for Plum Creek near Luling, TX with interval estimates of peak discharge based on total-least squares regression with San Marcos River at Luling

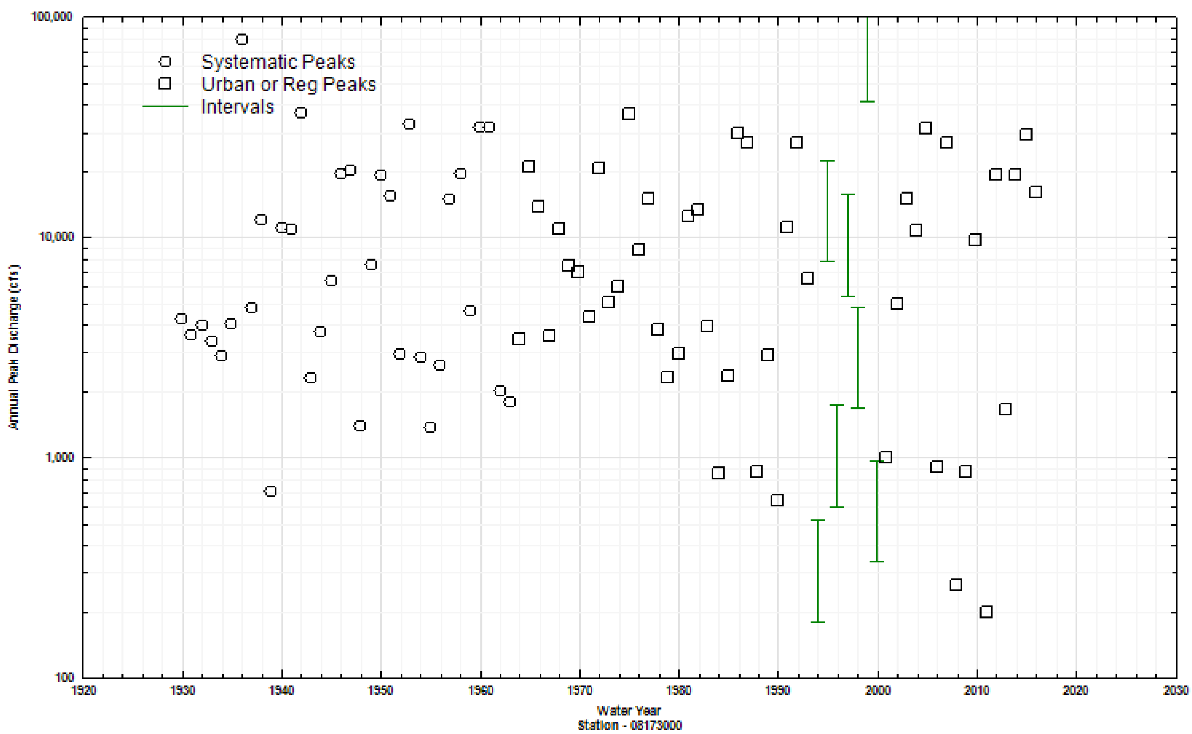

Figure 5.9: Annual Peak Streamflow Data for Plum Creek near Luling, TX with interval estimates of peak discharge based on total-least squares regression with Plum Creek at Lockhart, TX

Table 5.2 Streamflow-gaging stations intervals augmented by Total Least Squares Regression in the San Marcos River Basin, south-central, Texas

[--, not applicable; ft^3/s, cubic feet per second; "<=>", a compound symbol to denote an interval: low value < unobserved value < high value.]

Station number or water year	Either low estimate for discharge interval or point estimate		High estimate for discharge interval	Station number or water year	Either low estimate for discharge interval or point estimate		High estimate for discharge interval	Station number or water year	Either low estimate for discharge interval or point estimate		High estimate for discharge interval
	(ft^3/s)		(ft^3/s)		(ft^3/s)		(ft^3/s)		(ft^3/s)		(ft^3/s)
08172000 San Marcos River at Luling, Tex.				08173000 Plum Creek near Luling, Tex. (scenario number 1 with TLS regression with station 08172000)				08173000 Plum Creek near Luling, Tex. (scenario number 2 with TLS regression with station 08172400)			
1930	3,908	<=>	12,909	1994	178	<=>	516	1994	1,029	<=>	3,163
1931	3,311	<=>	10,938	1995	7,750	<=>	22,395	1995	3,122	<=>	9,598
1932	3,658	<=>	12,083	1996	594	<=>	1,718	1996	433	<=>	1,330
1933	3,128	<=>	10,334	1997	5,402	<=>	15,610	1997	9,371	<=>	28,808
1934	2,699	<=>	8,916	1998	1,662	<=>	4,804	1998	2,544	<=>	7,821
1935	3,727	<=>	12,311	1999	41,569	<=>	120,106	1999	87,644	<=>	269,424
1936	60,289	<=>	199,159	2000	334	<=>	966	2000	331	<=>	1,019
1937	4,379	<=>	14,466	--	--	--	--	--	--	--	--
1938	10,320	<=>	34,090	--	--	--	--	--	--	--	--
1939	721	<=>	2,382	--	--	--	--	--	--	--	--
08172400.01 Plum Creek at Lockhart, Tex. (alternative scenario for station 08172400)				08172400.01 Plum Creek at Lockhart, Tex. (alternative scenario for station 08172400)							
1930	1,395	<=>	4,274	1945	2,120	<=>	6,498	--	--	--	--
1931	1,158	<=>	3,549	1946	6,967	<=>	21,348	--	--	--	--
1932	1,295	<=>	3,969	1947	7,117	<=>	21,808	--	--	--	--
1933	1,086	<=>	3,329	1948	423	<=>	1,297	--	--	--	--
1934	920	<=>	2,821	1949	2,528	<=>	7,746	--	--	--	--
1935	1,322	<=>	4,053	1950	6,742	<=>	20,659	--	--	--	--
1936	30,131	<=>	92,324	1951	5,438	<=>	16,664	--	--	--	--
1937	1,585	<=>	4,857	1952	944	<=>	2,893	--	--	--	--
1938	4,151	<=>	12,720	1953	11,880	<=>	36,403	--	--	--	--
1939	209	<=>	640	1954	910	<=>	2,790	--	--	--	--
1940	3,787	<=>	11,604	1955	417	<=>	1,278	--	--	--	--
1941	3,714	<=>	11,381	1956	833	<=>	2,553	--	--	--	--
1942	13,623	<=>	41,742	1957	5,253	<=>	16,098	--	--	--	--
1943	729	<=>	2,235	1958	6,967	<=>	21,348	--	--	--	--
1944	1,199	<=>	3,674	--	--	--	--	--	--	--	--

Low estimate refers to a lower estimate of annual peak streamflow that is typically defined as minus one standard error of estimate from a total least squares (TLS) regression (as known as line of organic correlation) and a "high estimate" is the converse typically defined as plus one standard error of estimate from TLS. The "point estimate" represents an estimated annual peak streamflow from methods such as the drainage-area ratio method (Asquith and others, 2006). Values are deliberately listed to the nearest 1 ft3/s, which serves as an analyst-needed indicator of auxillary information being incorporated into the analyses. Additional details are described on a station-by-station in the text.

5.3. Statistical Flood Flow Frequency Results

This section presents the results of the statistical analysis of the annual peak streamflow data at each analyzed USGS station. Statistical flow frequency estimates, along with their associated uncertainty intervals, are presented in both graphical and tabular formats. Tables of flood flow frequency values with attendant confidence limits are listed in Table 5.3. This table contains the preferred values for the statistical analysis computed using USGS-PeakFQ with EMA-LPIII methods. Table 5.4 lists LPIII fits using B17B methods using exclusively the systematic record.

San Marcos River at San Marcos, Texas

The flood flow frequency for the San Marcos River at San Marcos is shown in Figure 5.10. The data for this station are perhaps the most problematic in this study for secure inference by statistical methods. The record is short and most of the peaks are close in magnitude to daily mean streamflows. The large discharge interval estimate for 2015 also contributes to interpretation difficulties as does the inference of the historical importance of the October 1998 event, which is certainly historically large outside the period of systematic record based on other stations in the area. The flood flow frequency curve begins its steep climb at about 1,000 ft3/s in accordance with the four observed peaks with the fifth (October 1999) likely plotting too much to the left because of a lack in historical information. The confidence limits are prodigiously wide and usefulness is inherently questionable.

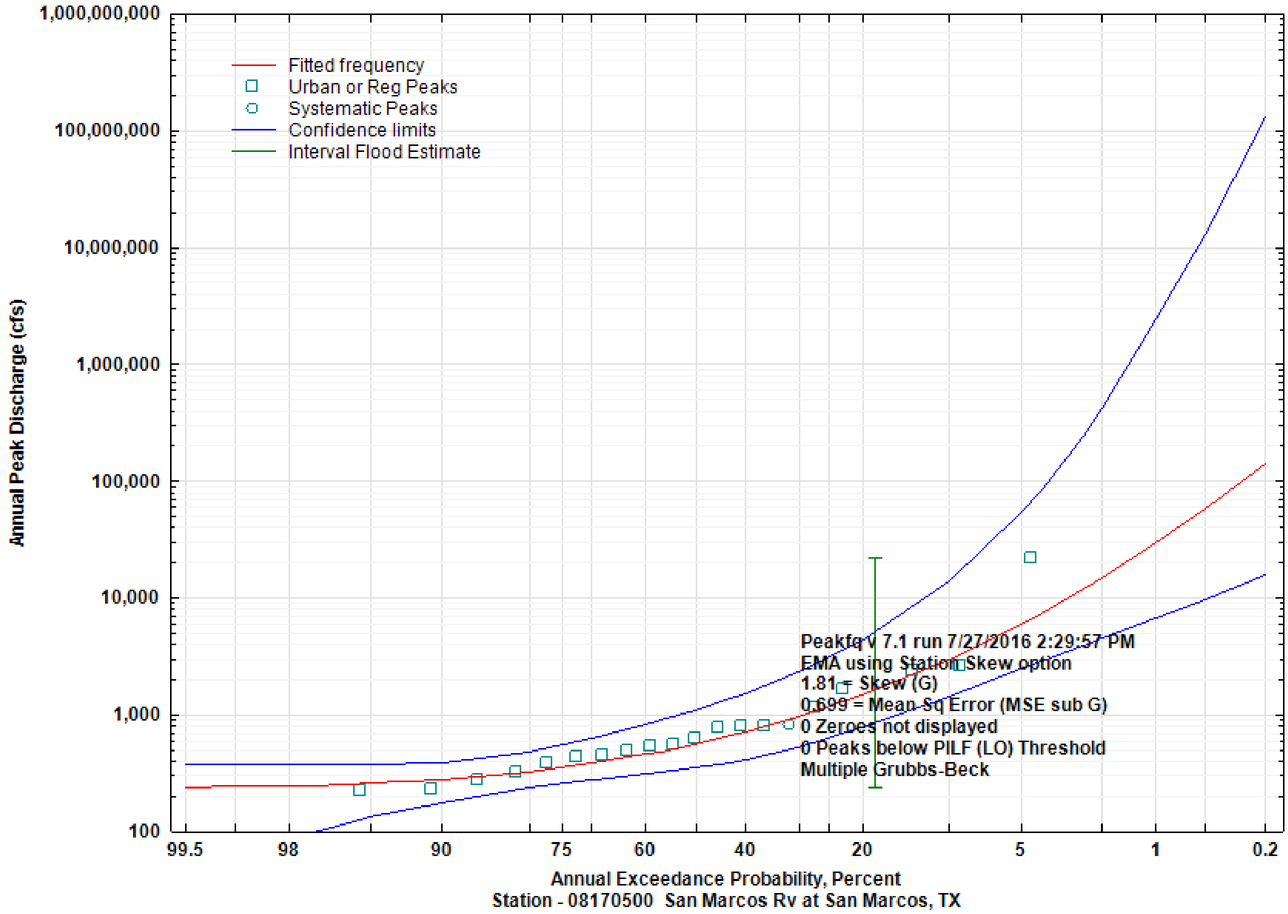

Figure 5.10: Peak Streamflow Frequency Curves for the San Marcos River at San Marcos, TX

Blanco River at Wimberley, Texas

The flood flow frequency for the Blanco River at Wimberley is shown in Figure 5.11. The long systematic record and extensive historical information lead to a reliable flood flow frequency curve. The largest event plots along the general trajectory of the curve. It could be that unspecified processes in the watershed tend to produce somewhat limiting rare peaks in the range of 80,000 to 120,000 ft3/s but the May 2015 peak substantiates the fact that considerably larger peaks, though rare, can occur. The low-outlier threshold can be seen conditionally removing peaks below about 1,000 ft3/s, and those data are seen to break away from the other data.

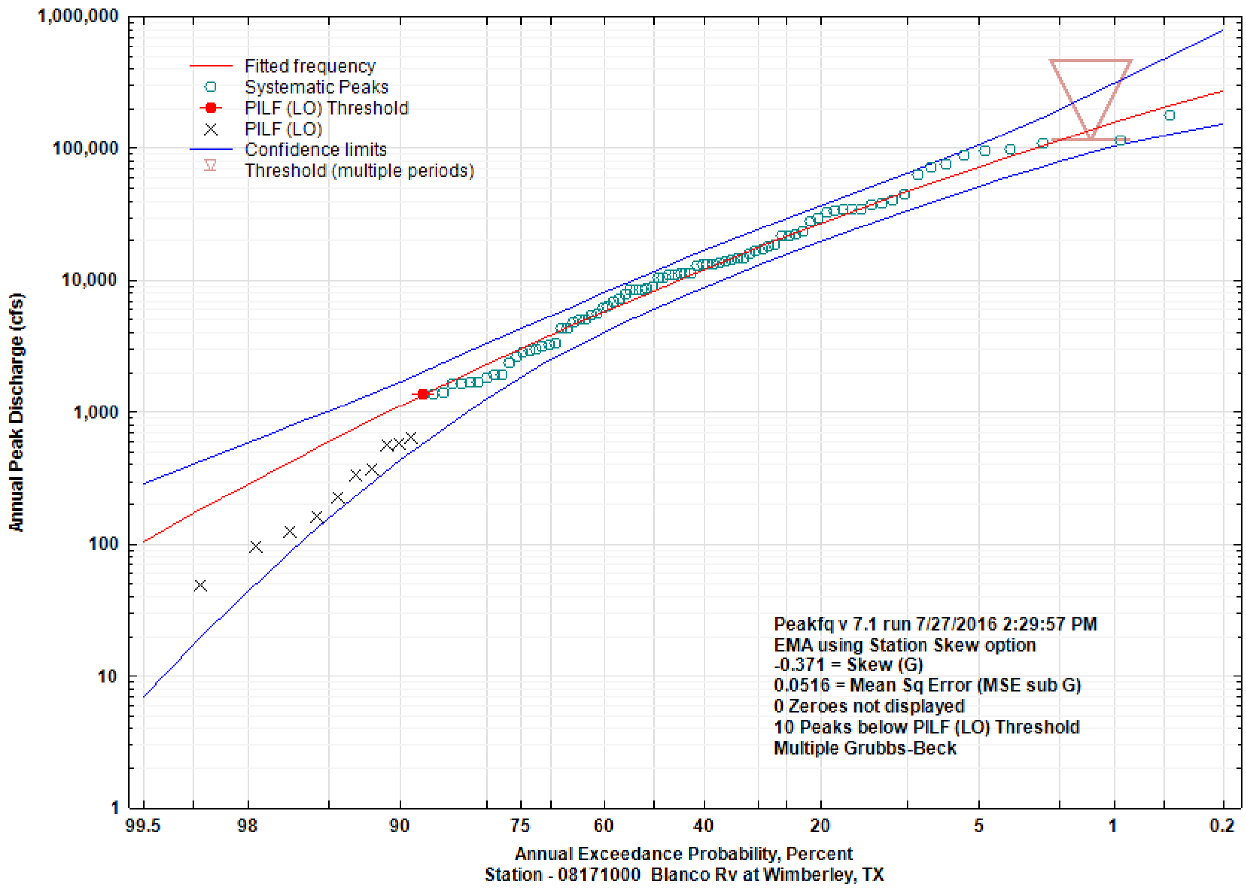

Figure 5.11: Peak Streamflow Frequency Curves for the Blanco River at Wimberley, TX

Blanco River near Kyle, Texas

The flood flow frequency for the Blanco River near Kyle is shown in Figure 5.12. The long systematic record and extensive historical information lead to a reliable flood flow frequency curve. The three blocks demarked in Figure 5.4 with a discharge threshold can be seen scattered within the empirical probabilities. The largest event plots just below the general trajectory of the curve. It could be that unspecified processes in the watershed tend to produce somewhat limiting rare peaks in the range of 80,000 to 120,000 ft3/s but the May 2015 peak substantiates the fact that considerably larger peaks, though rare, can occur. The rapid steepening of the data near AEP of 10 percent (40,000–90,000 ft3/s) suggests a population mixing. The low-outlier threshold can be seen conditionally removing peaks below about 4,000 ft3/s, and those data are seen to break away from the other data.

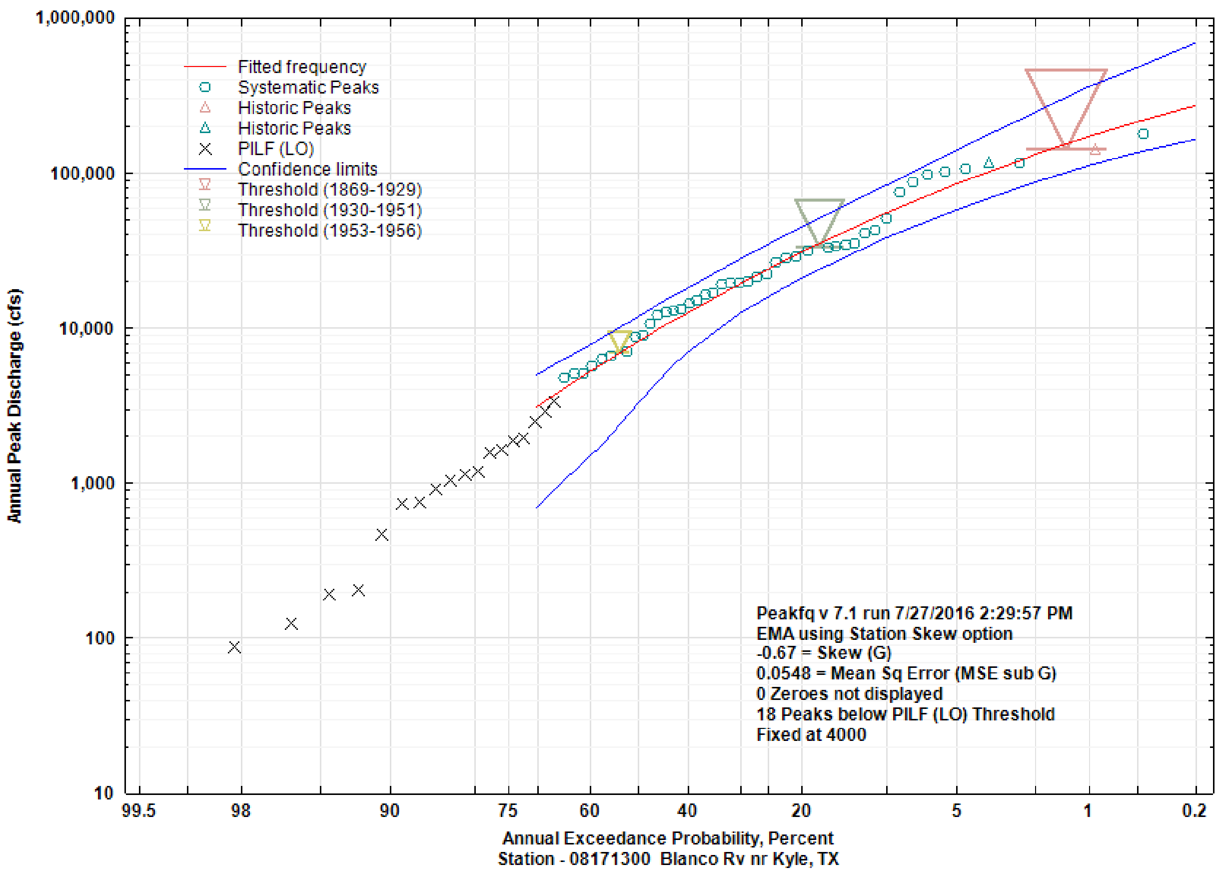

Figure 5.12. Peak Streamflow Frequency Curves for the Blanco River near Kyle, TX

San Marcos River at Luling, Texas

The flood flow frequency for the San Marcos River at Luling is shown in Figure 5.13. The long systematic record and extensive historical information lead to a reliable flood flow frequency curve. The single block demarked in Figure 5.13 with a discharge threshold can be seen affecting the empirical plotting of the largest event for which the fitted frequency curve nearly passes through. The discharge intervals are scattered amongst the empirical probabilities with the fitted curve generally bisecting (not deliberately) the intervals. No low outliers are identified.

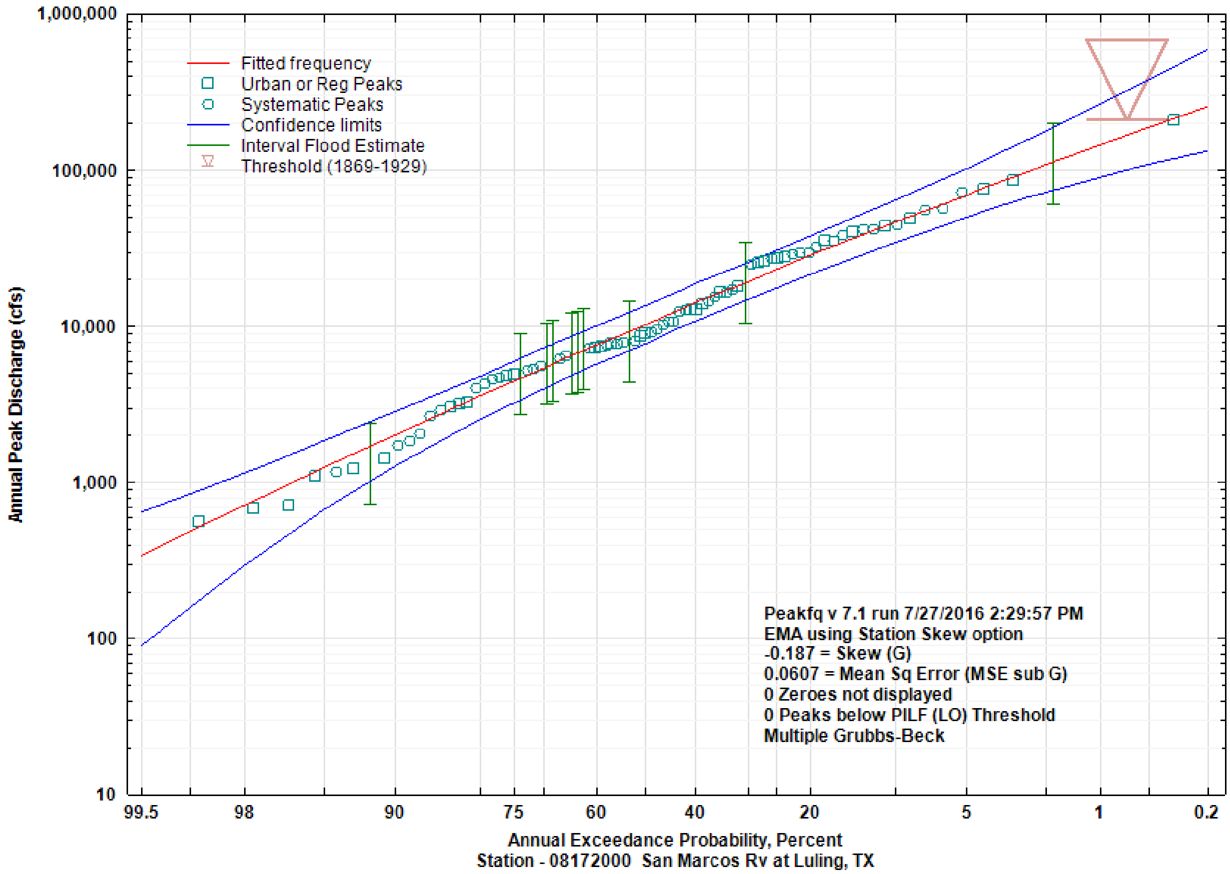

Figure 5.13. Peak Streamflow Frequency Curve Results for the San Marcos River at Luling, TX

Plum Creek at Lockhart, Texas

The flood flow frequency for Plum Creek at Lockhart is shown in Figure 5.14. Recall that an alternative analysis also is provided. The substantial systematic record leads to a reliable flood flow frequency curve. The low-outlier threshold can be seen conditionally removing peaks below about 1,400 ft3/s, and those data are seen to break away from the other data.

The alternative flood flow frequency for Plum Creek at Lockhart is shown in Figure 5.15. The substantial systematic record plus the inclusion of discharge intervals also leads to a reliable flood flow frequency curve. The same low-outlier threshold was used and can be seen conditionally removing peaks below about 1,400 ft3/s. The interval data was derived from TLS regression and the record at downstream Plum Creek near Luling. These intervals are an important addition, though numerous, to the analysis because the large 1936 event observed at Plum Creek near Luling is of great contextual interest. The alternative analysis with the discharge intervals (1930 to 1958) provides a common historical period of 87 years with Plum Creek near Luling. It is noteworthy for discussion with the next station (Plum Creek near Luling) that the October 1998 peak is 47,200 ft3/s at a stage of 23.09 ft.

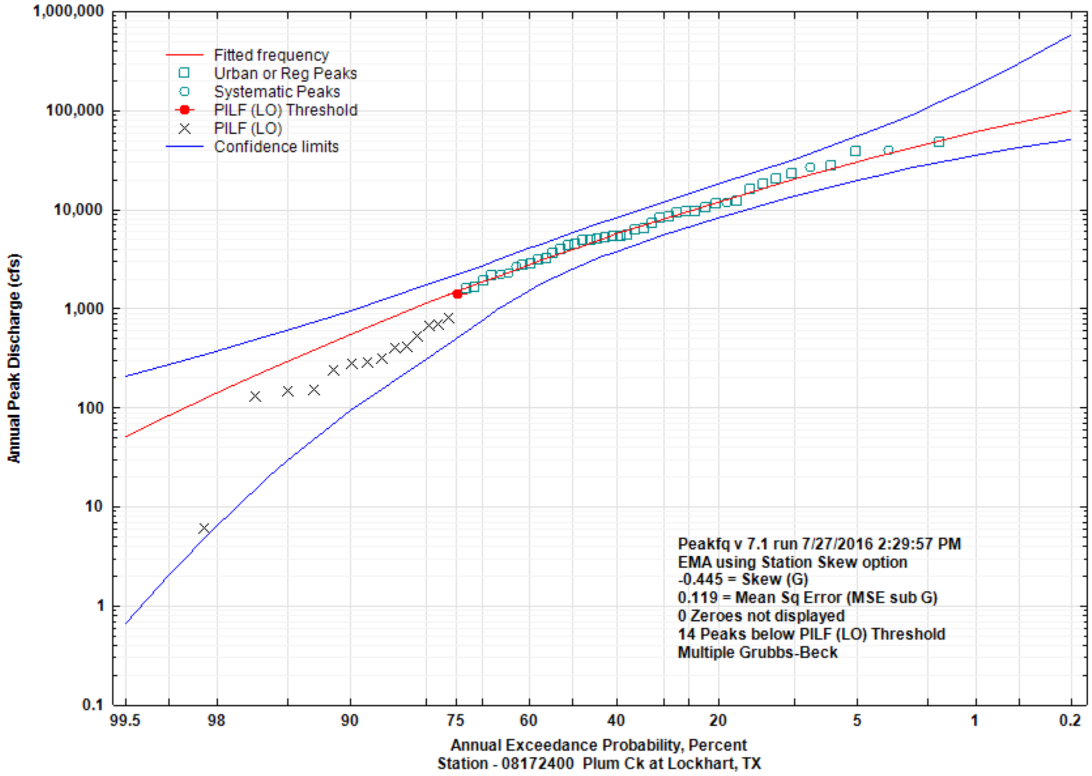

Figure 5.14: Peak Streamflow Frequency Curves for Plum Creek at Lockhart, TX

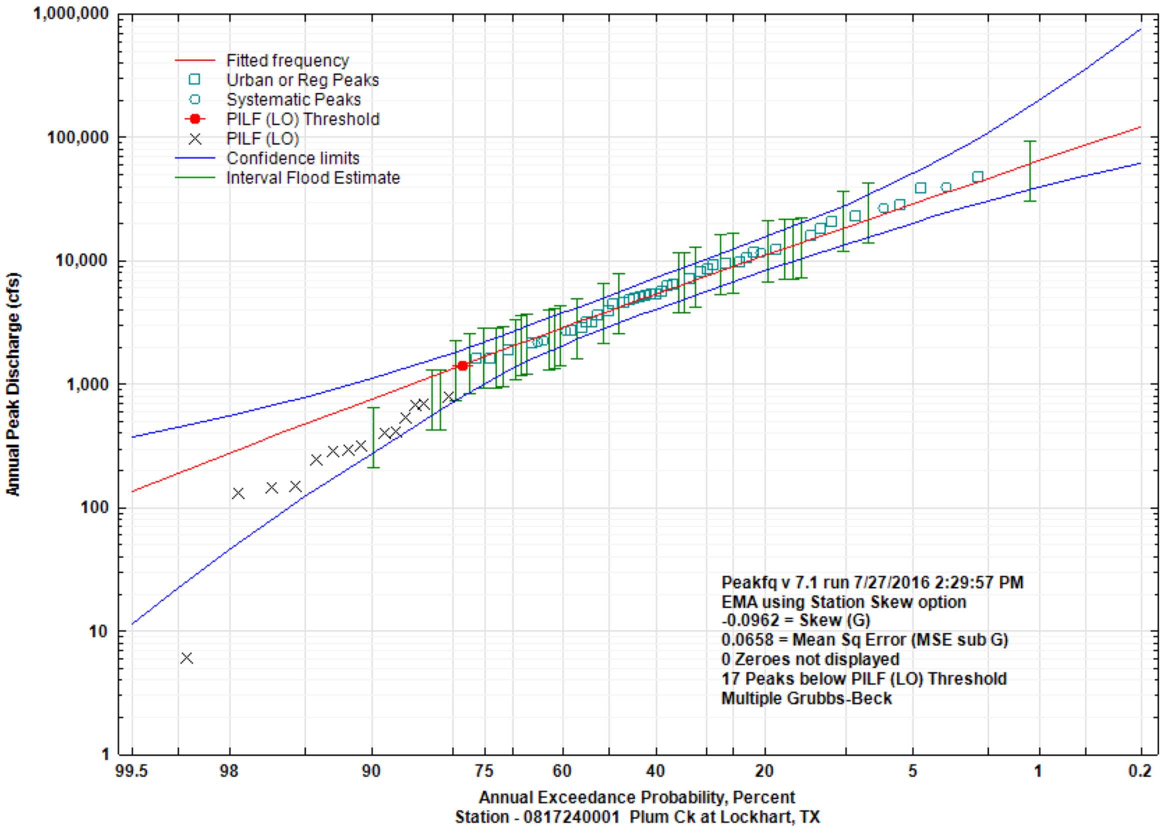

Figure 5.15: Peak Streamflow Frequency Curves for Plum Creek at Lockhart, TX (alternative analysis)

Plum Creek near Luling, Texas

The flood flow frequency for Plum Creek near Luling is shown in Figures 5.16 and 5.17. The extensive systematic record leads to a reliable flood flow frequency curve with the caveat that it is unknown how much contrast exists related to the unregulated and regulated record as flagged in USGS data (USGS, 2016). The period 1994 to 2000 is a gap in station operation and record is in-filled for this study with discharge interval data based on TLS regression with San Marcos River at Luling and separately with Plum Creek at Lockhart. The Plum Creek near Luling streamflow-gaging station has recorded the large 1936 peak (78,500 ft3/s at a stage of 30.70 ft) but the October 1998 event, which produced large peaks for other stations in the study area is not observed. It is difficult to identify a preferred application of TLS regression for gap in-fill for this station and hence the two shown in Figures 5.16 and 5.17 were both treated as plausible with the best estimate computed as the arithmetic mean of the confidence limit curves and the flood flow frequency curve being recommended for this study. These are the values listed in Table 5.3.

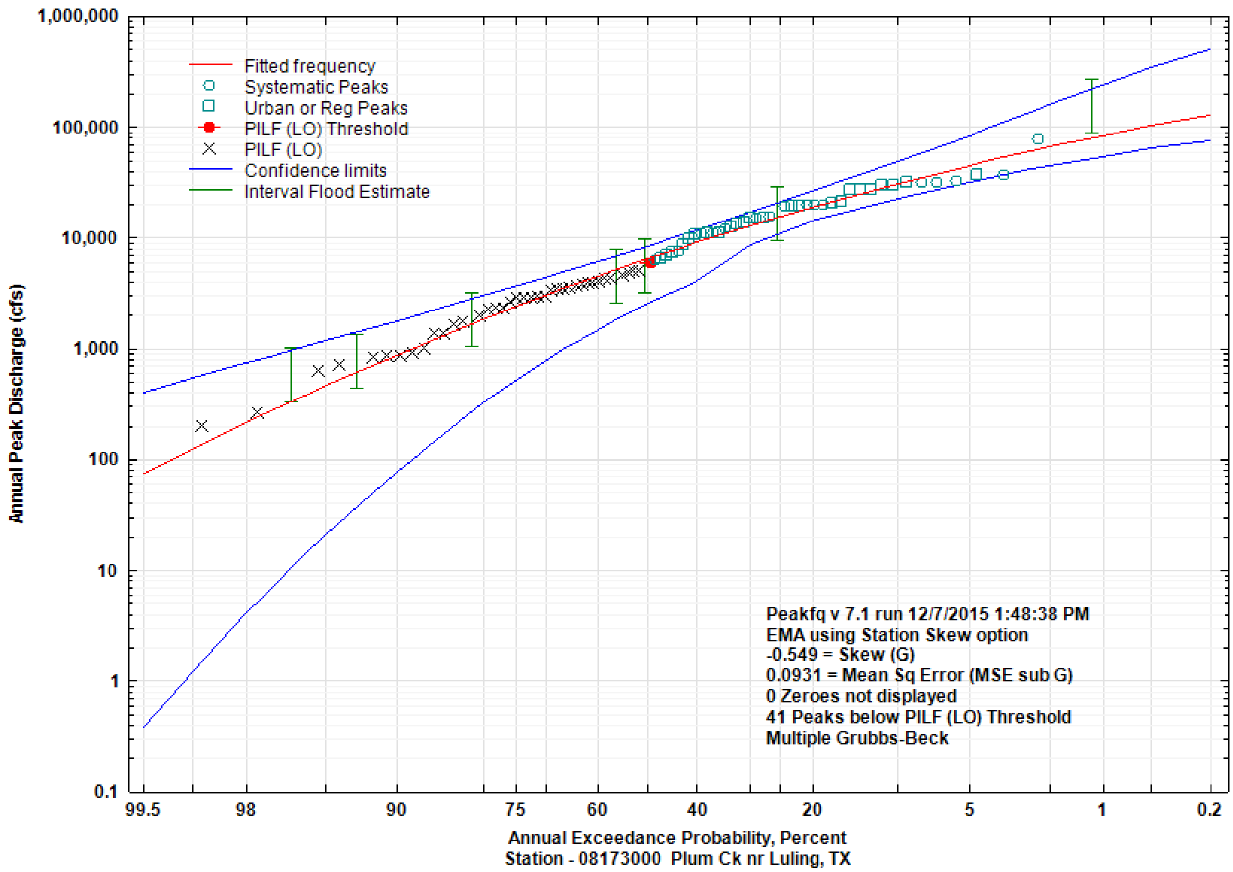

Figure 5.16: Peak Streamflow Frequency Curves for Plum Creek near Luling, TX with interval estimates of peak discharge based on total-least squares regression with San Marcos River at Luling

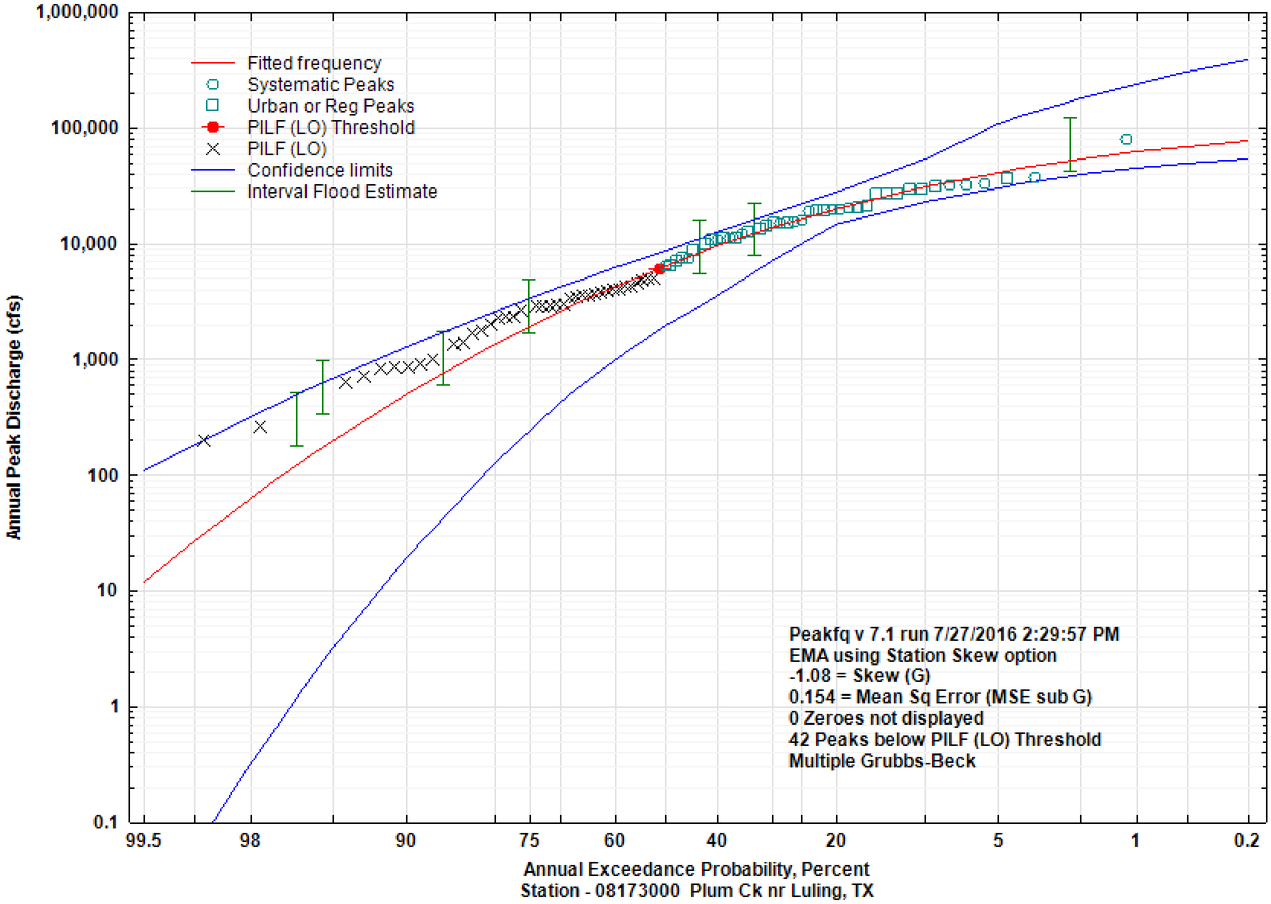

Figure 5.17: Peak Streamflow Frequency Curves for Plum Creek near Luling, TX with interval estimates of peak discharge based on total-least squares regression with Plum Creek at Lockhart, TX

Table 5.3: Statistically Estimated Annual Flood Flow Frequency Results for the six U.S. Geological Survey streamflow-gaging stations in the San Marcos River Basin, south-central, Texas based on the USGS-PeakFQ EMA-LPIII Computations

[--, not applicable; ft^3/s, cubic feet per second; %, percent; CI, confidence limit; Note, table contents derived from so-called EXP file (file extension name) of USGS-PeakFQ software output (USGS, 2014). The estimates are of primary interest and are accentuated using a bold typeface.]

Station number and name	Peak-streamflow frequency by corresponding average return period (recurrence interval) in years							
	2 year (ft^3/s)	5 year (ft^3/s)	10 year (ft^3/s)	25 year (ft^3/s)	50 year (ft^3/s)	100 year (ft^3/s)	200 year (ft^3/s)	500 year (ft^3/s)
08170500 San Marcos River at San Marcos, Tex.								
Lower 95%-CI	344	757	1,431	2,862	4,454	6,657	9,688	15,450
Estimate	**552**	**1,453**	**2,944**	**7,370**	**14,650**	**28,980**	**57,140**	**139,700**
Upper 95%-CI	1,083	4,252	13,740	83,170	409,500	2,398,000	12,750,000	126,800,000
08171000 Blanco River at Wimberley, Tex.								
Lower 95%-CI	5,931	19,310	33,540	57,500	78,710	101,200	123,800	153,000
Estimate	**8,284**	**26,530**	**46,410**	**81,240**	**114,400**	**153,700**	**199,300**	**269,400**
Upper 95%-CI	11,470	36,300	63,960	122,500	195,400	304,400	463,000	782,300
08171300 Blanco River near Kyle, Tex.								
Lower 95%-CI	3,319	20,930	37,780	64,960	87,970	111,600	134,900	163,700
Estimate	**8,110**	**30,450**	**54,810**	**95,290**	**131,100**	**170,400**	**212,500**	**271,100**
Upper 95%-CI	11,810	43,990	82,820	162,400	247,600	353,000	477,700	678,700
08172000 San Marcos River at Luling, Tex.								
Lower 95%-CI	7,736	21,140	34,270	54,850	72,020	89,930	108,200	132,500
Estimate	**10,250**	**27,890**	**46,100**	**77,540**	**107,600**	**143,600**	**186,100**	**253,500**
Upper 95%-CI	13,570	37,250	63,680	117,000	177,200	260,500	374,700	590,100
08172400 Plum Creek at Lockhart, Tex.								
Lower 95%-CI	2,481	8,107	13,410	21,680	28,440	35,220	41,840	50,090
Estimate	**3,915**	**11,850**	**19,990**	**33,480**	**45,700**	**59,600**	**75,130**	**98,020**
Upper 95%-CI	5,760	17,900	32,190	64,150	106,400	176,300	290,900	566,200
08172400.01* Plum Creek at Lockhart, Tex.								
Lower 95%-CI	2,892	8,103	13,460	22,410	30,360	39,100	48,440	61,520
Estimate	**3,863**	**10,900**	**18,540**	**32,400**	**46,240**	**63,490**	**84,650**	**119,600**
Upper 95%-CI	5,155	15,210	28,040	60,670	109,000	194,900	346,000	732,600
08173000 Plum Creek near Luling, Tex.								
Lower 95%-CI	2,220	14,230	22,760	33,600	41,520	49,010	56,000	64,300
Estimate	**6,370**	**19,190**	**30,610**	**46,850**	**59,580**	**72,480**	**85,430**	**102,600**
Upper 95%-CI	8,530	26,830	50,760	111,100	169,000	238,400	319,000	439,100

* Denotes the preferred analysis for this study through an alternative scenario in which record gaps have been bridged by interval estimates of annual peak streamflow because another streamgage on the same stream or a nearby long-record station was available for total-least squares regression. Further the extension ".01" shown is unique to this study and does not represent an official USGS station number.

Table 5.4: Statistically Estimated Annual Flood Flow Frequency Results for the six U.S. Geological Survey streamflow-gaging stations in the San Marcos River Basin, south-central, Texas based on the USGS-PeakFQ LPIII Computations using Only Systematic Record (no Historical Information Inclusion)

[--, not applicable alternative scenario has no meaning for systematic record computation (08172400); ft^3/s, cubic feet per second; %, percent; CI, confidence limit; Note, table contents derived from so-called EXP file (file extension name) of USGS-PeakFQ software output (USGS, 2014). The estimates are of primary interest and are accentuated using a bold typeface.]

Station number and name	Peak-streamflow frequency by corresponding average return period (recurrence interval) in years							
	2 year (ft^3/s)	5 year (ft^3/s)	10 year (ft^3/s)	25 year (ft^3/s)	50 year (ft^3/s)	100 year (ft^3/s)	200 year (ft^3/s)	500 year (ft^3/s)
08170500 San Marcos River at San Marcos, Tex.								
Lower 95%-CI	358	984	1,878	4,124	7,298	12,770	22,200	45,800
Estimate	**552**	**1,459**	**2,973**	**7,507**	**15,020**	**29,940**	**59,490**	**146,900**
Upper 95%-CI	813	2,400	5,821	19,480	49,030	123,700	312,100	1,060,000
08171000 Blanco River at Wimberley, Tex.								
Lower 95%-CI	6,978	20,930	36,420	65,280	94,950	132,900	180,800	262,500
Estimate	**8,796**	**26,950**	**48,600**	**91,410**	**137,700**	**199,400**	**279,900**	**422,900**
Upper 95%-CI	11,090	35,920	68,340	137,600	217,400	329,200	482,100	767,600
08171300 Blanco River near Kyle, Tex.								
Lower 95%-CI	9,455	26,340	43,390	72,560	100,400	133,800	173,600	237,000
Estimate	**12,390**	**35,260**	**60,320**	**106,100**	**152,300**	**210,100**	**281,400**	**399,900**
Upper 95%-CI	16,240	49,630	90,400	171,900	260,100	377,000	528,800	795,000
08172000 San Marcos River at Luling, Tex.								
Lower 95%-CI	8,468	22,930	36,780	59,210	79,480	102,700	129,100	169,000
Estimate	**10,730**	**29,700**	**49,200**	**82,550**	**114,000**	**151,400**	**195,000**	**263,100**
Upper 95%-CI	13,620	40,010	69,680	124,200	178,600	246,100	327,900	460,700
08172400 Plum Creek at Lockhart, Tex.								
Lower 95%-CI	3,310	8,483	13,650	22,560	31,200	41,800	54,690	75,870
Estimate	**4,234**	**11,050**	**18,440**	**32,080**	**46,080**	**64,010**	**86,700**	**125,600**
Upper 95%-CI	5,412	15,070	26,730	50,290	76,350	111,800	159,000	245,000
08172400.01* Plum Creek at Lockhart, Tex.								
Lower 95%-CI	--	--	--	--	--	--	--	--
Estimate	--	--	--	--	--	--	--	--
Upper 95%-CI	--	--	--	--	--	--	--	--
08173000 Plum Creek near Luling, Tex.								
Lower 95%-CI	5,009	13,330	19,870	28,380	34,520	40,330	45,750	52,310
Estimate	**6,480**	**17,700**	**27,080**	**39,780**	**49,230**	**58,330**	**66,980**	**77,580**
Upper 95%-CI	8,440	24,510	39,060	59,800	75,840	91,700	107,100	126,300

* Denotes the preferred analysis for this study through an alternative scenario in which record gaps have been bridged by interval estimates of annual peak streamflow because another streamgage on the same stream or a nearby long-record station was available for total-least squares regression. Further the extension ".01" shown is unique to this study and does not represent an official USGS station number.

5.4. Changes to Flow Frequency Estimates over Time

Statistically based flow frequency estimates are dependent on observational data and historical information. Examples of changes to flood flow frequency estimates over time are provided for the Blanco River at Wimberley and near Kyle along with the San Marcos River at Luling in Figures 5.18, 5.19, and 5.20. Each of these examples vividly illustrates that there is a progression in statistical estimates over time. Peaks outside the period of record are not shown. For example, the 1952 peak at Blanco River near Kyle is 115,000 ft^3/s but not shown in Figure 5.19 because systematic station record begins in 1957.

The USGS-PeakFQ software when setup for data processing by EMA does not readily facilitate computations such as those required for similar graphics. The computations involved were based on fitting the LPIII to the L-moments (Asquith, 2011a,b) of the data points shown from a given year backwards in time. The computations included a minimum of 10 years. As a result, the actual starting year varies amongst the figures. The results of USGS-PeakFQ as listed in Table 5.3 provide the ordinates for 2016 (right-most side of the figures), and logarithmic-derived offsets between the L-moment-based LPIII fit in 2016 were used to adjust the curves in prior years for each of the four recurrence intervals.

Blanco River at Wimberley

In Figure 5.18 flow estimates spike in response to three substantial peaks clustered in time (1952, 1957, and 1958) and the great increase centered circa 1960 is also impart showing sensitivity to a smaller sample size. The increase circa 2016 is relatively larger than that seen 15 years earlier because the 2015 event is also the peak of record bound by 2014 and 2016 peaks which are of the same general magnitude as seen six prior times in the record not counting 2015. As the record length increases for a station given other factors remaining relatively constant (landuse for example), the curves should vary year to year to a lesser degree for the simple reason that proportionally less information is included with each successive year.

Blanco River near Kyle

In Figure 5.19 a trough in the estimates ending circa 2000 with the October 1998 and 2002 events clustering and being substantial floods of a magnitude not seen since the late 1950s (1957 and 1958). The estimates substantially increase circa 2016 with observation of the 2014, 2015, and 2016 peaks. Collectively, the five large peaks in the past 17 years act to substantially change relative estimates when compared to Blanco River at Wimberley because Wimberley has considerably longer systematic record. The vertical axis limits are not the same between the two Blanco River stations and hence purely visual comparison of curve “jumps” is not possible.

San Marcos River at Luling

Relative impact of record length and magnitudes of substantial floods impacts can be seen in Figure 5.20. A striking feature of the San Marcos River is the general growth in the 1% annual chance (100-yr) estimate with a period of stabilization until the inclusion of the October 1998 event (206,000 ft3/s with a stage of 36.55 ft; 1999 water year and plotted as such). This is a remarkable event with a discharge substantially larger than all others, though potentially exceeded by the unknown discharge for the 1929 event with a stage of about 37.1 ft and the unknown discharge for the 1869 event with a stage of about 40.4 ft. The 1% annual chance (100-yr) estimate oscillated around 90,000 ft3/s for about 35 years (circa 1962 to 1998) in which the largest flood on record at that time was 57,000 ft3/s in 1952. Since 1999, there have been three years with flood peaks (2004, 2015, and 2016) that exceeded all observed flood events prior to 1998 by substantial margins. Collectively, these contribute to very recent (2015 and 2016) increases in the 1% annual chance (100-yr) estimate. The October 1998 event however is by far the contributing reason for modern estimates to be on the order of say 100,000 ft3/s more than understanding prior to that event.

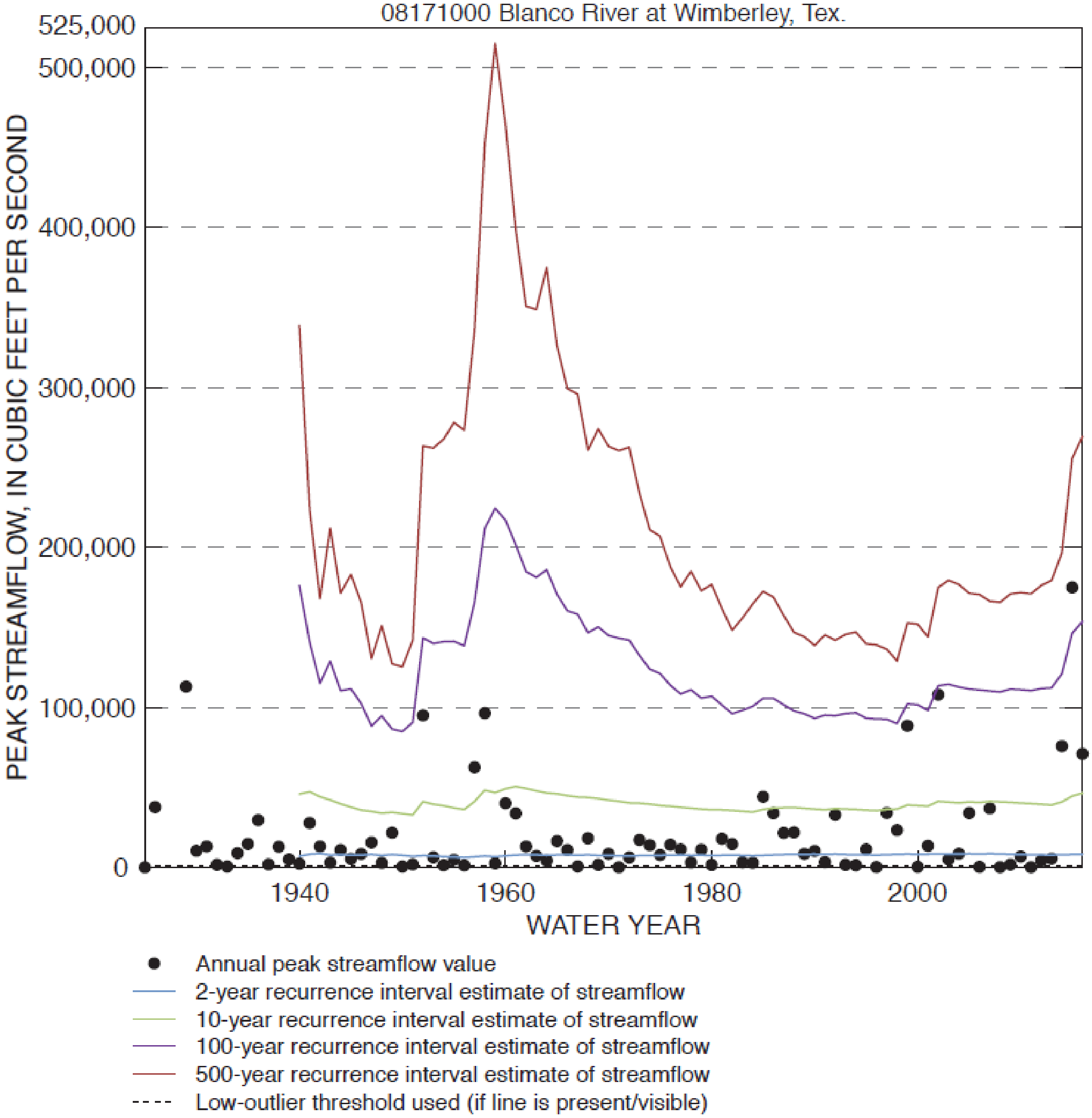

Figure 5.18: Statistical Frequency Flow Estimates versus Time for the Blanco River at Wimberley, TX

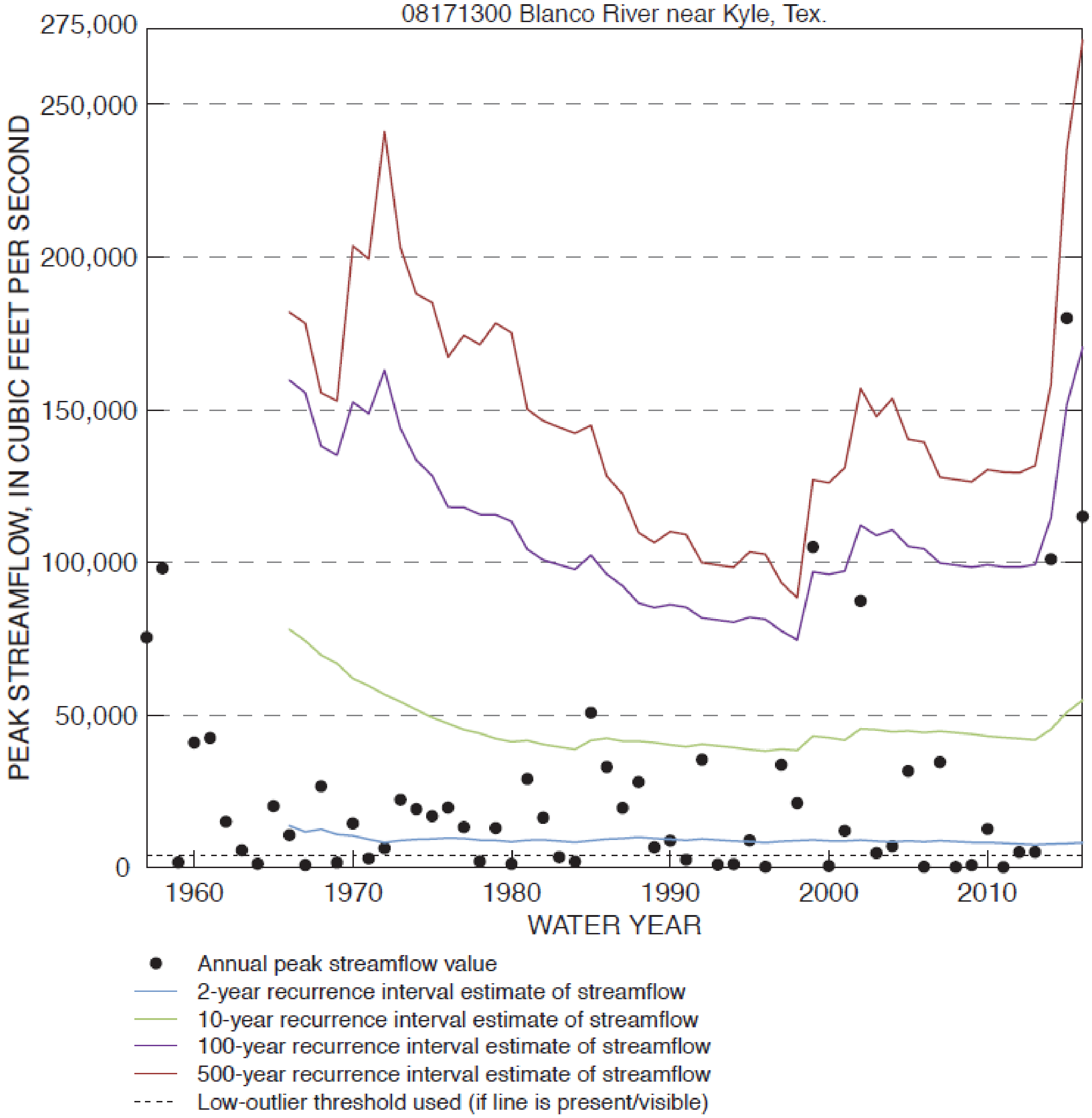

Figure 5.19: Statistical Frequency Flow Estimates versus Time for the Blanco River near Kyle, TX

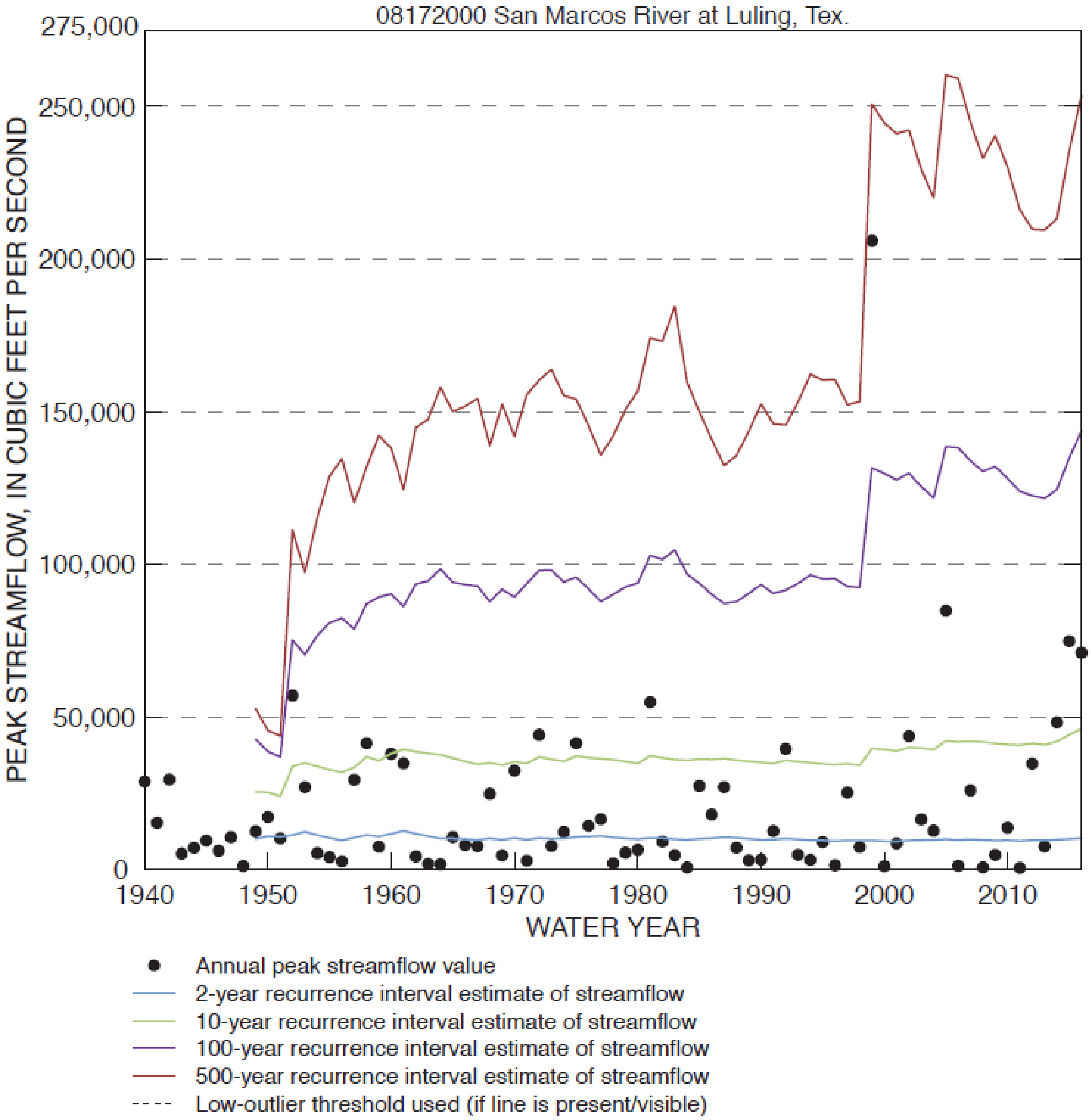

Figure 5.20: Statistical Frequency Flow Estimates versus Time for the San Marcos River at Luling, TX

5.5. Influence of Climatic Variability

Annual peak streamflow do not occur at the same time or under the same conditions in each water year. Each year the annual peak streamflow for a station is generated in the watershed by immensely complex interactions between weather patterns and discrete rainfall events, physical aspects of the terrain coupled with the amalgamation of the arrival time of flood waves amongst tributaries, and conditional storage conditions and infiltration capacities. Storage conditions represent both manmade structures (reservoirs and detention basins), but also nonpoint storage such as initial watershed losses and depression storage. Conversely, some water years might effectively have such limited rainfall input that residual waters draining for many months or longer periods of previous rainfall episodes would not be considered as "flood events." The conditional status of the watershed is influenced by general climate conditions because such conditions express antecedent moisture conditions.

A sensitivity study was conducted to evaluate the effects of climate variability on the streamflow-gaging station record. Runoff and soil loss rates in Texas have been observed to vary greatly from one storm to another, depending on the antecedent moisture conditions of the soil at the time of the storm. Therefore, for this sensitivity test, the Palmer Drought Severity Index (PDSI) at the time of each recorded annual peak was used to divide the streamflow-gaging stations record into a “wet” peak series and a “dry” peak series. For each of the six streamflow-gaging stations, a threshold of PDSI demarking dry and wet conditions for the month of each annual peak streamflow was selected as PDSI = 1.4, which approximately bifurcates the data. An annual peak occurring in a month having PDSI less than or equal to 1.4 was classified as a dry condition peak and conversely an annual peak occurring in a month having PDSI greater than 1.4 was classified as a wet condition peak. In particular, the PDSI is used to distinguish between periods of below typical and abundant moisture conditions. Details about the PDSI are described by Palmer (1965) and other information is available from National Centers for Environmental Information ([NCEI], 2016 a,b,c,d).

The Blanco River at Wimberley streamflow-gaging station is selected as an example. Annual peak streamflow data split between wet and dry conditions is plotted (Figure 5.21) using empirical annual exceedance probabilities and compared to the annual exceedance probabilities of all of the data sourced from USGS-PeakFQ EMA-LPIII analysis (Table 5.3). In this figure, the blue line represents an estimated frequency curve for the wet condition data, and the red line represents an estimated frequency curve from the dry condition data. From this graph, one can see that there is significant separation between the wet and dry curves. The two largest observed flows (filled red circles) near the dry condition curve were from the 1952 and 2014 events. Both of these events occurred during extremely dry periods. Had those storm events occurred during wet climate conditions, their peak discharges likely would have been much larger. Two take away messages are (1) it appears that climate variation contributes to greater separation for small recurrence intervals (say 2 and 5 year recurrence intervals), and (2) the separation between the two curves diminishes as probability decreases. Other stations had similar results.

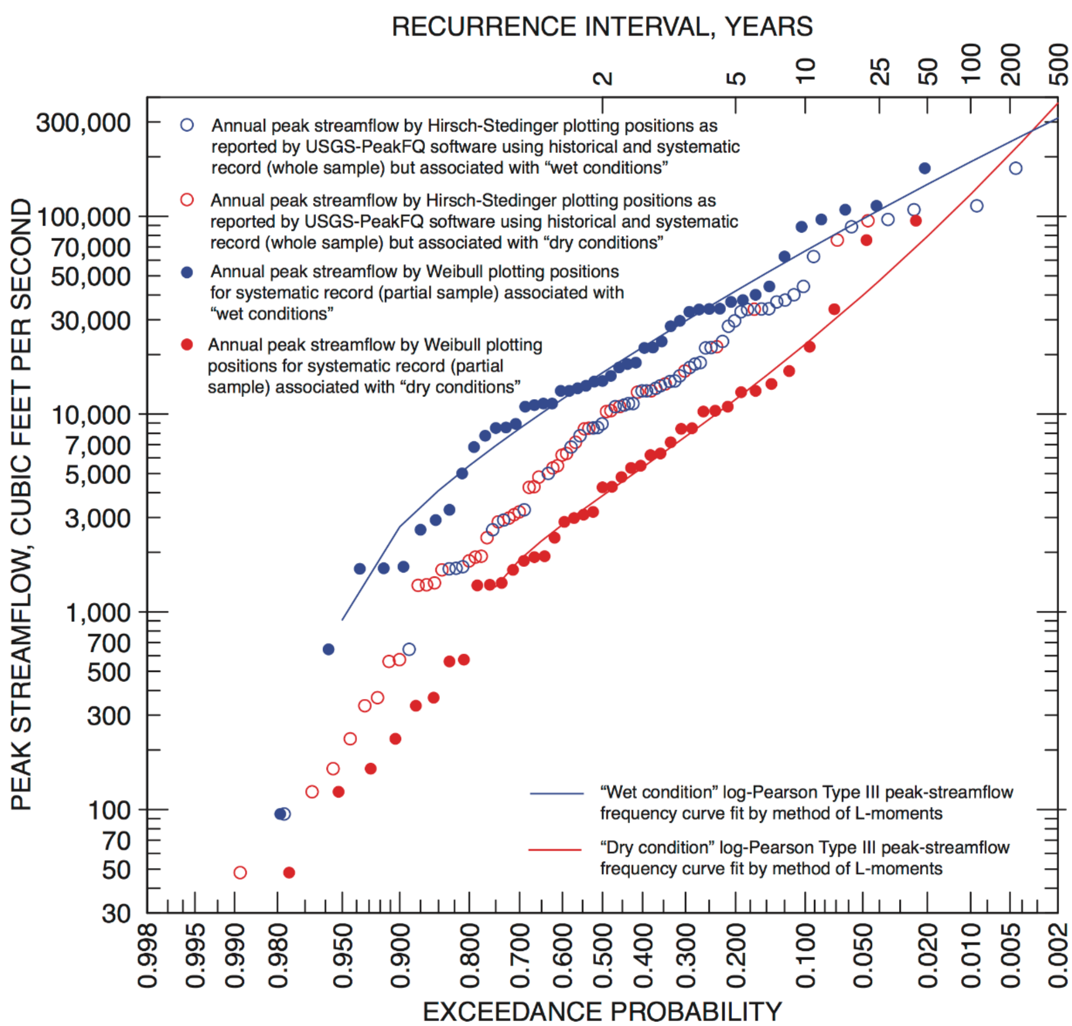

Figure 5.21: Effects of Climate Variability on the Flow Frequency Curve at Wimberley, TX

5.6. Effects of Regulation on Statistical Estimates of Flood Flow Frequency

The USGS database of annual peak streamflow (USGS, 2016) has only a rudimentary data qualification scheme identifying peaks as regulated ("code 6") or unregulated (non-code 6). The USGS code 6 designation is based on whether about 10 percent of the contributing drainage area is affected by reservoirs. For this study, all available peaks were analyzed regardless of code 6 designation.

Asquith (2001) provides a very general statistical overview study of the effects of flood-storage capacity per unit area on the L-moments (Asquith, 2011, a,b) of annual peak streamflow data. Asquith's results suggest that effects of regulation as implicated by flood-storage capacity per unit area become detectable at about 100 acre-feet per square mile (acre-ft/mi^2) and with possible substantial impact at about 400 acre-ft/mi^2. Asquith developed regression estimates of the change in mean annual peak streamflow as a function of this flood-storage capacity which suggest that higher dimensionless L-moments remain unaffected. The impact is relative to drainage area size and in turn the mean peak streamflow at a given station.

InFRM team members from USACE computed temporal changes in normal capacity and flood-storage capacities from the NID. The cumulative differences between flood-storage and normal capacity are referred to as cumulative flood storages, and the values divided by contributing drainage area are listed in Table 5.1 for the last year of analysis (2016) as well as the estimated effect of cumulative flood storage as computed from Asquith's equations (Asquith, 2011, fig. 11a). These can help guide interpretations of statistical flood flow frequency estimates in this chapter.

The results listed in Table 5.1 indicate that annual peak streamflow data relative for Blanco River at Wimberley, Blanco River at Kyle, and San Marcos River at Luling are not anticipated to be substantially influenced by flood-storage capacity in their respective watersheds. The San Marcos River at San Marcos has the highest relative impact of about –271 ft^3/s, which when compared to a general magnitude of annual peak of about 750 ft^3/s is of the same order of about 36 percent (100 * 271 / 750). The two Plum Creek stations have relative impacts of about –532 ft^3/s (Lockhart) and –1,142 ft^3/s (Luling) compared to general magnitude of annual peak of about 3,500 ft^3/s (Lockhart) and 4,700 ft^3/s (Luling) are of about 15 percent (Lockhart) and 24 percent (Luling). So a demonstrable impact is likely. However, considering that the 1% annual chance (100-yr) estimates for the two Plum Creek stations are about 60,000 ft^3/s, it seems that the small flood-water retarding structures in the watersheds have relatively lesser impact on high magnitude and rare peak streamflows. Large-scale flood-control regulation in the watersheds is lacking. Further evaluation of the impacts of regulation in all the watersheds of this study seems beyond statistical analysis and hydrologic rainfall-runoff modeling would be informative.

5.7. Comparison of Flood Flow Frequency Estimates to Prior Work

Asquith and Roussel (2009) provide regional regression equations (Asquith and Roussel, 2009; Table 3) to estimate flood flow frequency based on the contributing drainage area, main-channel slope, and mean annual precipitation at the station location. The estimates from the applicable equations are listed in Table 5.5. In the presence of substantial observational data such as that available for this study and relative to the flood flow frequency results computed from observed data shown elsewhere in this chapter, the regional regression estimates should be considered less applicable and subject to standard errors on the order of 1/3 log-cycle (base10, Asquith and Roussel, 2009, Table 3).

The equations by Asquith and Roussel (2009) are based on large-scale automated data processing of annual peak streamflows across Texas for hundreds of stations. The data were through water year 2007. Many large magnitude peaks though have been observed in recent years for stations in the San Marcos River basin study area. An expected consequence could be that the regional regression equations have current relative bias of underestimation. Comparison of the 1% annual chance (100-yr) event results in Table 5.5 to the recommended statistical estimates of flood flow frequency for this study (Table 5.3) shows such underestimation.

Table 5.5: Estimates of Flood Flow Frequency from Regional Regression Equations by Asquith and Roussel (2009) for Six U.S. Geological Survey Streamflow-Gaging Stations in the San Marcos River Basin, south-central, Texas.

[ft^3/s, cubic feet per second; --, not available because main-channel slope is not available.]

Station number	Peak-streamflow frequency by corresponding average return period (recurrence interval) in years								"OmegaEM" from Asquith and Roussel (2009)
	2 year (ft^3/s)	5 year (ft^3/s)	10 year (ft^3/s)	25 year (ft^3/s)	50 year (ft^3/s)	100 year (ft^3/s)	200 year (ft^3/s)	500 year (ft^3/s)	
08170500	--	--	--	--	--	--	--	--	--
08171000	9,953	23,678	34,659	53,444	70,865	92,086	116,448	155,329	0.146
08171300	9,940	23,608	34,667	53,482	70,921	92,156	116,608	155,532	0.144
08172000	13,158	29,770	43,043	64,972	84,934	108,724	136,052	177,932	0.149
08172400	4,238	9,785	14,274	21,785	28,633	36,898	46,346	61,354	0.141
08173000	7,375	16,723	24,234	36,677	47,971	61,458	76,905	100,863	0.146

The regional equations by Asquith and Thompson (2008) imply in very general terms that the ratio of discharges is equal to the ratio of respective contributing drainage areas raised to the an exponent of 1/2 (square root). This is a form of the drainage-area ratio method further investigated by Asquith and others (2006). The square-root of area form of the method could be used to adjust estimated flood flow frequencies in Table 5.3 to ungaged locations with a limitation of about 1.5 log-cycle difference in respective drainage areas (Asquith and others, 2006, p. 14). Though for the current study a limit of about 1.0 log-cycle (order of magnitude) would be more cautious. Multiple estimates for an ungaged location could be accommodated by weighted-mean computation.

6.0 Rainfall-Runoff Modeling in HEC-HMS

While statistical analysis of the gage record is a valuable means of estimating the magnitude of flood frequency flows at the gage, watershed rainfall-runoff modeling is often used to estimate the rare frequency events whose return periods exceed the gaged period of record as well as to account for non-stationary watershed conditions such as urbanization, reservoir storage and regulation, and climate variability. Rainfall-runoff modeling also provides a means of estimating flood frequency flows at other locations throughout the watershed that do not coincide with a stream flow gage. Rainfall-runoff watershed modeling is used to simulate the physical processes that occur during storm events that move water across the land surface and through the streams and rivers.

In the second phase of the multi-layered hydrologic analysis, a watershed model was built for the San Marcos River Basin with input parameters that represented the physical characteristics of the watershed. The rainfall-runoff model for the basin was completed using the basin-wide HEC-HMS model developed for the Guadalupe Basin CWMS Implementation as a starting point. This model was further refined by adding additional detailed data, updating the land use, and calibrating the model to multiple recent flood events. Through calibration, the updated HEC-HMS model was verified to accurately reproduce the response of the watershed to multiple recent observed storm events, including those similar in magnitude to a 1% annual chance (100-yr) storm. Finally, frequency storms were built using the latest published frequency rainfall depths (Asquith, 2004) and were run through the verified model, yielding the best available estimates of the 1% annual chance (100-yr) and other frequency peak flows at various locations throughout the basin.

6.1. HEC-HMS Model from the Guadalupe CWMS Implementation

The HEC-HMS model from the Guadalupe CWMS Implementation was used as the starting point for the current study. The CWMS model contained 19 subbasins in the San Marcos River Basin totaling about 1,359 square miles. The subbasins were delineated using the HEC-GeoHMS program and utilized 30-meter NED terrain data. The Guadalupe CWMS HEC-HMS model used the following methods.

- **Losses** – Initial and Constant
- **Transform** – Snyder Unit Hydrograph
- **Baseflow** – Recession
- **Routing** – Modified Puls
- **Computation Interval** – 15 minutes

A map of the Guadalupe CWMS subbasins from the San Marcos portion of the model are shown in Figure 6.1. More information on the CWMS model development is given in the final CWMS report for the Guadalupe River Basin (USACE, 2014).

6.2. Updates to the HEC-HMS Model

To better define the hydrology of the San Marcos River Basin, additional subbasin breaks were added to the original CWMS delineation. The total number of subbasins in the basin was increased from 19 to 47. Additional subbasins were added in two areas: the Blanco River and Sink Creek. These areas were selected for additional detail due to their locations just upstream of the developed areas of Wimberley and San Marcos.

The Blanco River is an important part of the basin as it tends to be the primary source of flooding for the cities of Wimberley and San Marcos, Texas. Additional subbasins were added to the Blanco River basin in order to give better definition to the rainfall patterns and the timing of the tributaries entering the Blanco River. In total, the number of subbasins in the Blanco River basin was increased from six to 29. The new subbasin break points were chosen based on several factors which include: the locations of significant tributaries, the locations of the new USGS stream flow gages that were installed after the flood events of 2015, and the locations of developed areas or major road crossings.

Sink Creek is a tributary to the San Marcos River just upstream of the city of San Marcos. Flood flows from the Sink Creek Watershed are significantly attenuated by the presence of three NRCS dams in the watershed. In order to better account for the effects of these dams, subbasin breaks were added at the locations of the dams. The physical data for these NRCS dams, including elevation-capacity curves, spillway and outlet structures, were also added to the HEC-HMS model. In total the number of subbasins on Sink Creek was increased from one subbasin to six. The final subbasin map for the San Marcos River Basin HEC-HMS model is shown in Figure 6.2.

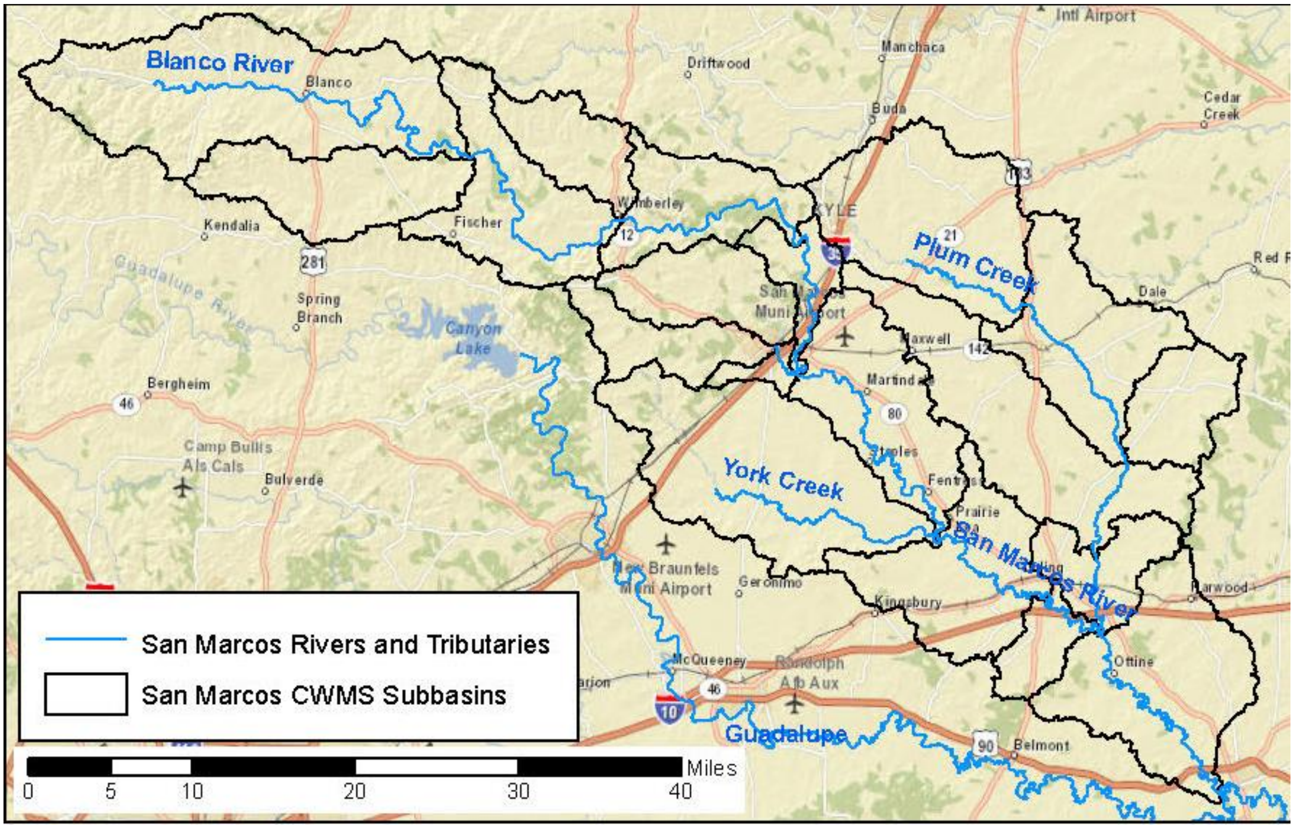

Figure 6.1: Guadalupe CWMS subbasins for the San Marcos River Basin

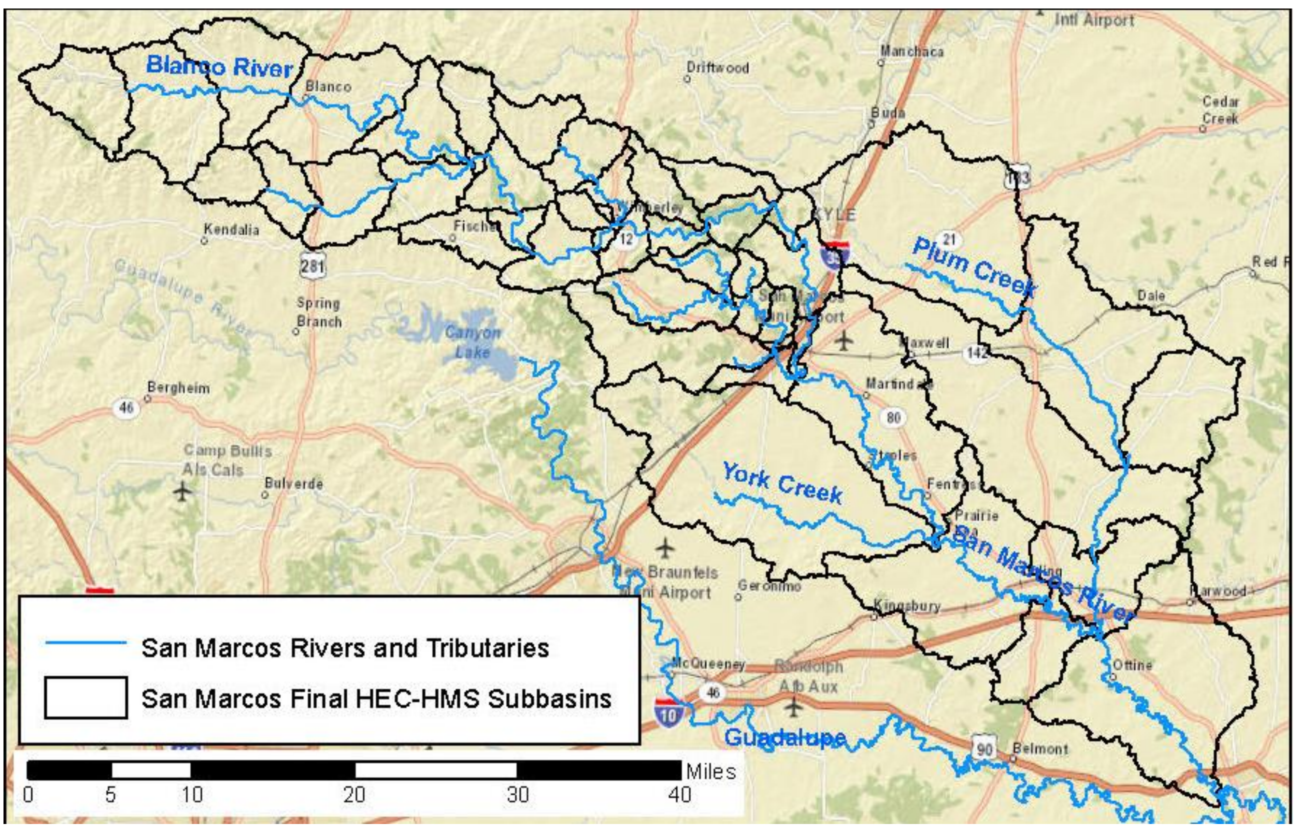

Figure 6.2: Final HEC-HMS subbasins for the San Marcos River Basin

After breaking out the additional subbasins, detailed routing data was added to the HEC-HMS model for the associated new river reaches and for other reaches where detailed hydraulic modeling was available. The Modified Puls routing method was used for all of the reaches throughout the basin model. Modified Puls is a routing method that calculates the change in flow through the reach based on the volume of floodplain storage through that reach. For the San Marcos River basin, the necessary storage-discharge curves for the Modified Puls routing were extracted from the best available detailed hydraulic models, which included detailed HEC-RAS models of the Blanco River, San Marcos River, Plum Creek and Sink Creek from the Lower Guadalupe Feasibility Study. These HEC-RAS models were built off of detailed LiDAR topographic data and included other detailed information such as bridge and channel surveys. For more information on the development of those hydraulic models, please refer to the hydraulic modeling appendices from the Lower Guadalupe Feasibility Study (Halff, 2014 and 2015). Modified Puls routing data for other reaches, such as the Blanco River and Little Blanco River in Blanco County, which were not included in the Lower Guadalupe Feasibility study area, were extracted from existing detailed HEC-1 hydrologic models from the 1988 draft Hays County Flood Insurance Study.

6.3. HEC-HMS Model Initial Parameters

The San Marcos River HEC-HMS model contains 47 subbasins totaling about 1,359 square miles. The subbasins were delineated using the HEC-GeoHMS program and utilized 30-meter NED terrain data. The San Marcos River HEC-HMS model used the same methods as the Guadalupe CWMS model, which including initial and constant losses, Snyder unit hydrograph transform parameters, recession baseflows, and Modified Puls routing. The sources of the initial estimates for these parameters are described below.

- **Initial Loss and Constant Loss Rate** – The USACE Fort Worth District equations for losses were used. These equations utilize estimates of percent sand in the soil to develop initial deficit and constant loss rates for different frequency storm events. The 25-yr losses were used as a starting point. Percent sand estimates were obtained from the NRCS SSURGO soil data.
- **Percent Impervious** – The percent impervious values were developed based on the 2011 NLCD percent developed impervious dataset.
- **Snyder Transform Parameters** – The time to peak and peaking coefficients were developed from the USACE Fort Worth District urban curves based on length and slope watershed characteristics extracted from HEC-GeoHMS, percent urban values taken from the 2011 NLCD, and percent sand values taken from the NRCS SSURGO soils data. From this data, the following regional equation, which was developed as part of the Fort Worth District urban studies (Nelson, 1979) (Rodman, 1977) (USACE, 1989), was used to calculate lag time:
  log (tp) = .383log (L*Lca/(Sst ^ .5))+(Sand*(log1.81-log.92)+log.92)-(BW*Urban./100)
  where: tp = Snyder's lag time (hours)
  L = longest flow path within the subbasin (miles)
  Lca = distance along the stream from the subbasin centroid to outlet (miles)
  Sst = stream slope over reach between 10% and 85% of L (feet per mile)
  Sand = percentage of sand factor as related to the permeability of the soils
  (0% Sand = low permeability, 100% Sand = high permeability)
  BW = log(tp) bandwidth between 0% and 100% urbanization = 0.266 (log hours)
  Urban. = percentage urbanization factor
- **Baseflow Parameters** – Initial baseflow parameters were taken from the existing USACE Guadalupe CWMS HEC-HMS model.
- **Routing Parameters (Modified Puls)** – Storage-discharge curves for the Modified Puls routing were extracted from the best available detailed hydraulic and hydrologic models. Initial subreach values were estimated based on an average travel time through the reach.

The initial subbasin and routing parameters that were entered into the HEC-HMS model are show in Tables 6.1 through 6.4. Some of these parameters were adjusted during calibration. Final parameters are shown in Section 6.5.

Table 6.1: Subbasin Area, Percent Impervious and Initial Estimate of Loss Rates

Subbasin Name	Drainage Area (sq mi)	Percent Impervious (%)	Initial Loss (in)	Constant Loss (in/hr)
Blanco_S010	26.44	0.0	1	0.15
Blanco_S020	40.84	0.0	1	0.15
Blanco_S030	35.89	0.3	1	0.14
Blanco_S040	43.58	1.1	1	0.14
Blanco_S050	22.38	0.2	1	0.14
LittleBlanco_S010	12.83	0.2	1	0.15
LittleBlanco_S020	13.41	0.2	1	0.15
LittleBlanco_S030	24.15	0.6	1	0.14
LittleBlanco_S040	18.31	0.2	1	0.15
Blanco_S060	1.18	0.1	1	0.15
WanslowCr_BR_S010	13.37	0.4	1	0.15
Blanco_S070	16.42	0.4	1	0.15
Blanco_S080	5.86	0.6	1	0.15
CarpersCr_BR_S010	15.35	0.9	1	0.15
Blanco_S090	19.06	1.0	1	0.15
Blanco_S100	1.59	2.7	1	0.15
WilsonCr_BR_S010	5.34	0.6	1	0.15
Blanco_S110	0.93	12.5	1	0.15
CypressCr_BR_S010	15.02	0.2	1	0.15
CypressCr_BR_S020	15.11	1.0	1	0.15
CypressCr_BR_S030	8.01	3.9	1	0.15
Blanco_S120	8.49	1.7	1	0.15
Blanco_S130	6.95	0.2	1	0.15
LoneManCr_BR_S010	12.37	0.3	1	0.15
Blanco_S140	9.85	0.1	1	0.15
HalifaxCr_BR_S010	12.92	0.1	1	0.14
Blanco_S150	6.65	0.2	1	0.14
Blanco_S160	20.39	2.2	1	0.14
Blanco_S170	3.57	16.4	1	0.15
SinkCk_S010	23.53	0.0	1	0.12
SinkCk_S020	9.89	0.0	1	0.12
SinkCk_S030	4.34	0.0	1	0.12
SinkCk_S040	5.61	3.0	1	0.12
SanMarcos_S005	5.58	6.0	1	0.12
SanMarcos_S008	0.98	46.0	1	0.12
PurgatoryCr_S010	37.13	2.0	1	0.12
SanMarcos_S010	7.99	16.0	1	0.13
SanMarcos_S020	82.34	1.0	1	0.13
YorkCr_S010	142.92	1.0	1	0.12
SanMarcos_S030	82.38	1.0	1	0.13
SanMarcos_S040	22.89	1.0	1	0.14
PlumCr_S010	111.30	2.0	1	0.12
PlumCr_S020	83.29	1.0	1	0.13
TenneyCr_S010	39.82	0.0	1	0.14
PlumCr_S030	117.08	0.0	1	0.13
PlumCr_S040	37.34	1.0	1	0.13
SanMarcos_S050	108.37	0.0	1	0.14

Table 6.2: Initial Estimates of Snyder's Transform Parameters

Subbasin Name	% Urban	% Sand	Lag Time (hr)	Peaking Coefficient
Blanco_S010	0	83	3.2	0.72
Blanco_S020	0	85	3.9	0.72
Blanco_S030	0	77	2.9	0.72
Blanco_S040	1	72	5.2	0.72
Blanco_S050	0	68	4.9	0.72
LittleBlanco_S010	0	86	2.2	0.72
LittleBlanco_S020	0	82	2.6	0.72
LittleBlanco_S030	1	70	2.9	0.72
LittleBlanco_S040	0	89	4.2	0.72
Blanco_S060	0	93	0.9	0.72
WanslowCr_BR_S010	0	93	3.2	0.72
Blanco_S070	1	90	2.9	0.72
Blanco_S080	2	87	2.7	0.72
CarpersCr_BR_S010	1	95	4.4	0.72
Blanco_S090	1	92	3.1	0.72
Blanco_S100	5	90	1.2	0.72
WilsonCr_BR_S010	1	94	2.6	0.72
Blanco_S110	15	91	1.0	0.72
CypressCr_BR_S010	0	94	2.7	0.72
CypressCr_BR_S020	1	95	2.5	0.72
CypressCr_BR_S030	4	92	3.2	0.72
Blanco_S120	2	94	2.1	0.72
Blanco_S130	2	95	2.9	0.72
LoneManCr_BR_S010	0	100	4.8	0.72
Blanco_S140	2	93	2.9	0.72
HalifaxCr_BR_S010	0	80	4.6	0.72
Blanco_S150	2	81	2.8	0.72
Blanco_S160	3	74	3.6	0.72
Blanco_S170	21	100	3.9	0.72
SinkCk_S010	0	85	4.4	0.7813
SinkCk_S020	0	84	3.4	0.7813
SinkCk_S030	0	86	1.1	0.7813
SinkCk_S040	3	79	1.4	0.7813
SanMarcos_S005	7	71	1.5	0.7813
SanMarcos_S008	54	26	0.8	0.7813
PurgatoryCr_S010	2	84	8.5	0.7813
SanMarcos_S010	20	43	1.9	0.7813
SanMarcos_S020	3	33	8.6	0.7813
YorkCr_S010	3	18	6.5	0.7813
SanMarcos_S030	1	60	6.9	0.7813
SanMarcos_S040	2	78	5.0	0.7813
PlumCr_S010	5	13	12.1	0.7813
PlumCr_S020	2	33	5.3	0.7813
TenneyCr_S010	1	61	4.0	0.7813
PlumCr_S030	2	36	6.8	0.7813
PlumCr_S040	2	66	4.6	0.7813
SanMarcos_S050	1	76	13.0	0.7813

Table 6.3: Initial Estimates of Baseflow Parameters

Subbasin Name	Initial Discharge (cfs / sq mi)	Recession Constant	Ratio to Peak
Blanco_S010	0.2	0.92	0.03
Blanco_S020	0.2	0.92	0.03
Blanco_S030	0.2	0.92	0.03
Blanco_S040	0.2	0.92	0.03
Blanco_S050	0.2	0.92	0.03
LittleBlanco_S010	0.2	0.92	0.03
LittleBlanco_S020	0.2	0.92	0.03
LittleBlanco_S030	0.2	0.92	0.03
LittleBlanco_S040	0.2	0.92	0.03
Blanco_S060	0.2	0.92	0.03
WanslowCr_BR_S010	0.2	0.92	0.03
Blanco_S070	0.2	0.92	0.03
Blanco_S080	0.2	0.92	0.03
CarpersCr_BR_S010	0.2	0.92	0.03
Blanco_S090	0.2	0.92	0.03
Blanco_S100	0.2	0.92	0.03
WilsonCr_BR_S010	0.2	0.92	0.03
Blanco_S110	0.2	0.92	0.03
CypressCr_BR_S010	0.2	0.92	0.03
CypressCr_BR_S020	0.2	0.92	0.03
CypressCr_BR_S030	0.2	0.92	0.03
Blanco_S120	0.2	0.89	0.03
Blanco_S130	0.2	0.89	0.03
LoneManCr_BR_S010	0.2	0.89	0.03
Blanco_S140	0.2	0.89	0.03
HalifaxCr_BR_S010	0.2	0.89	0.03
Blanco_S150	0.2	0.89	0.02
Blanco_S160	0.2	0.89	0.02
Blanco_S170	0.2	0.89	0.02
SinkCk_S010	0.3	0.89	0.05
SinkCk_S020	0.3	0.89	0.05
SinkCk_S030	0.3	0.89	0.05
SinkCk_S040	0.3	0.89	0.05
SanMarcos_S005	0.3	0.89	0.05
SanMarcos_S008	0.3	0.89	0.05
PurgatoryCr_S010	0.3	0.89	0.05
SanMarcos_S010	0.3	0.89	0.05
SanMarcos_S020	0.3	0.89	0.05
YorkCr_S010	0.3	0.79	0.1
SanMarcos_S030	0.3	0.89	0.05
SanMarcos_S040	0.3	0.89	0.05
PlumCr_S010	0.3	0.79	0.1
PlumCr_S020	0.3	0.79	0.1
TenneyCr_S010	0.3	0.79	0.1
PlumCr_S030	0.3	0.79	0.1
PlumCr_S040	0.3	0.79	0.1
SanMarcos_S050	0.3	0.89	0.05

Table 6.4: Modified Puls Routing Data

HEC-HMS Reach Name	Storage-Discharge Source	Initial Subreaches
Blanco_R020F	Hays Co FIS HEC-1	2
Blanco_R020H	Hays Co FIS HEC-1	3
Blanco_R030J	Hays Co FIS HEC-1	1
Blanco_R030L	Hays Co FIS HEC-1	2
Blanco_R030M	Hays Co FIS HEC-1	1
Blanco_R040O	Hays Co FIS HEC-1	2
Blanco_R040P	Hays Co FIS HEC-1	3
Blanco_R040R	Hays Co FIS HEC-1	5
Blanco_R050S	Hays Co FIS HEC-1	3
Blanco_R050T	Hays Co FIS HEC-1	5
LittleBlanco_R020V	Hays Co FIS HEC-1	2
LittleBlanco_R030W	Hays Co FIS HEC-1	3
LittleBlanco_R030X	Hays Co FIS HEC-1	3
LittleBlanco_R040Y	Hays Co FIS HEC-1	5
Blanco_R060Z	Hays Co FIS HEC-1	1
Blanco_R070	Blanco River HEC-RAS	5
Blanco_R080	Blanco River HEC-RAS	4
Blanco_R090	Blanco River HEC-RAS	4
Blanco_R100	Blanco River HEC-RAS	2
Blanco_R110	Blanco River HEC-RAS	1
CypressCr_R0204C	Hays Co FIS HEC-1	1
CypressCr_R0206C	Hays Co FIS HEC-1	1
CypressCr_R0206CL	Hays Co FIS HEC-1	1
CypressCr_R02010C	Hays Co FIS HEC-1	1
CypressCr_R03012C	Hays Co FIS HEC-1	1
CypressCr_R03014C	Hays Co FIS HEC-1	1
CypressCr_R03016C	Hays Co FIS HEC-1	1
Blanco_R120	Blanco River HEC-RAS	2
Blanco_R130	Blanco River HEC-RAS	5
Blanco_R140	Blanco River HEC-RAS	5
Blanco_R150	Blanco River HEC-RAS	4
Blanco_R160a	Blanco River HEC-RAS	2
Blanco_R160b	Blanco River HEC-RAS	3
Blanco_R170	Blanco River HEC-RAS	6
SinkCk_R010	Upper San Marcos HEC-RAS	1
SinkCk_R020	Upper San Marcos HEC-RAS	1
SinkCk_R030	Upper San Marcos HEC-RAS	1
SinkCk_R040	Upper San Marcos HEC-RAS	1
SinkCk_R050	Upper San Marcos HEC-RAS	1
SanMarcos_R003	Upper San Marcos HEC-RAS	1
SanMarcos_R005	Upper San Marcos HEC-RAS	1
SanMarcos_R007	Upper San Marcos HEC-RAS	1
SanMarcos_R020	San Marcos River HEC-RAS	8
SanMarcos_R030	San Marcos River HEC-RAS	5
SanMarcos_R040	San Marcos River HEC-RAS	2
PlumCr_R010	Plum Creek HEC-RAS	8
PlumCr_R020	Plum Creek HEC-RAS	6
SanMarcos_R050	San Marcos River HEC-RAS	7

6.4. HEC-HMS Model Calibration

After building the model, the InFRM team calibrated the model to verify it was accurately simulating the response of the watershed to a range of observed flood events, including large events similar to a 1% annual chance (100-yr) flood. A total of eight recent storm events were used to fine tune the model. The model calibration and verification process undertaken during this study exceeds the standards of a typical FEMA floodplain study.

Table 6.5: Observed Flood Events Simulated in the San Marcos Watershed Model

Date of Flood	Recorded Peak Flow (cfs)		
	Blanco River at Wimberley	Blanco River near Kyle	San Marcos River at Luling
Oct-1998	88,500	105,000	206,000
Nov-2001	108,000	87,300	43,700
Nov-2004	34,000	31,600	84,800
Mar-2007	36,900	34,500	25,900
Jan-2012	-	-	34,700
Oct-2013	75,800	101,000	48,200
May-2015	175,000	180,000	74,800
Oct-2015	71,000	115,000	71,000

For these storms, the National Weather Service (NWS) hourly rainfall radar data allowed the team to fine tune the watershed model through detailed calibration. Prior to the late 1990s, the NWS data was not available for use during earlier modeling efforts. The final model results accurately simulated the expected response of the watershed, as it reproduced the timing, shape, and magnitudes of the observed floods very well. Figures 6.3 through 6.10 illustrate the total depth of rain for each calibration storm and how that rain was distributed spatially throughout the San Marcos River watershed. These plots were extracted from the HEC-MetVue program for visualizing and processing rainfall data.

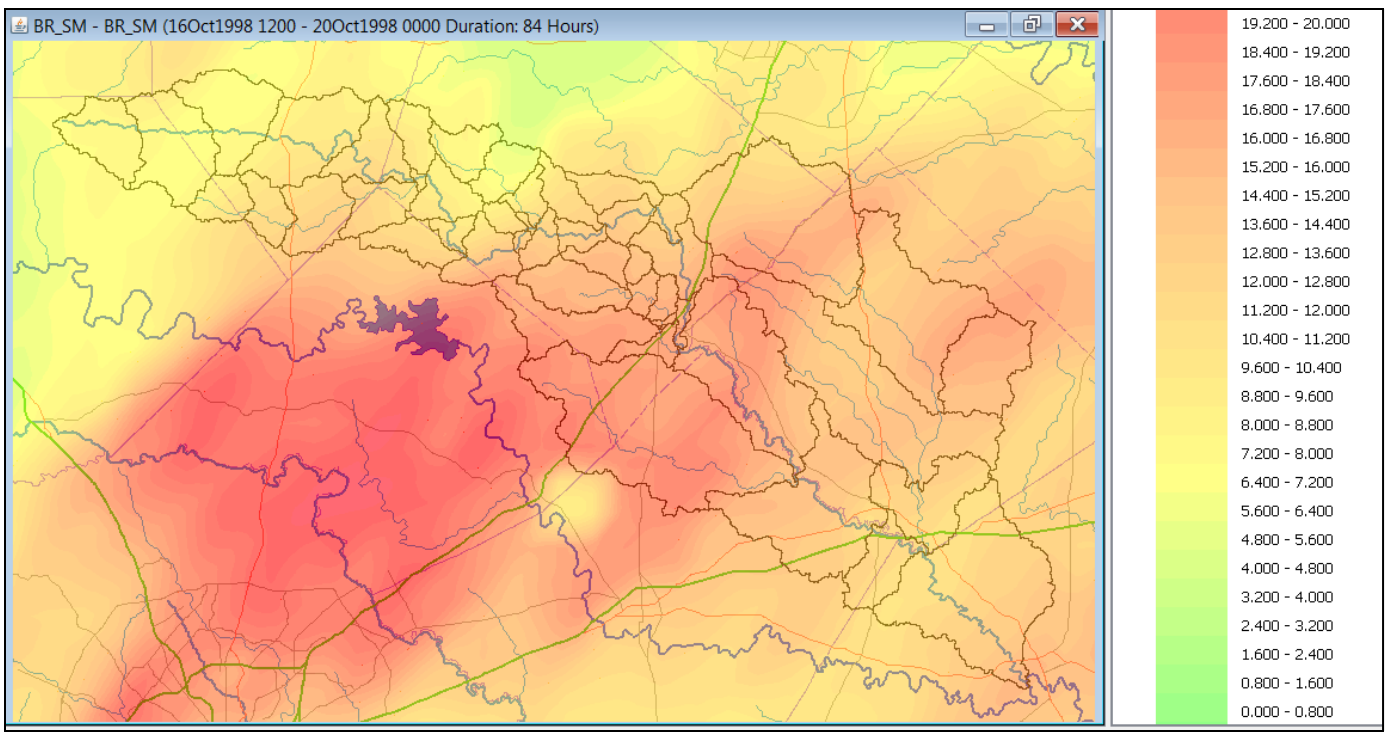

Figure 6.3: Rainfall Depths (inches) for the October 1998 Calibration Storm

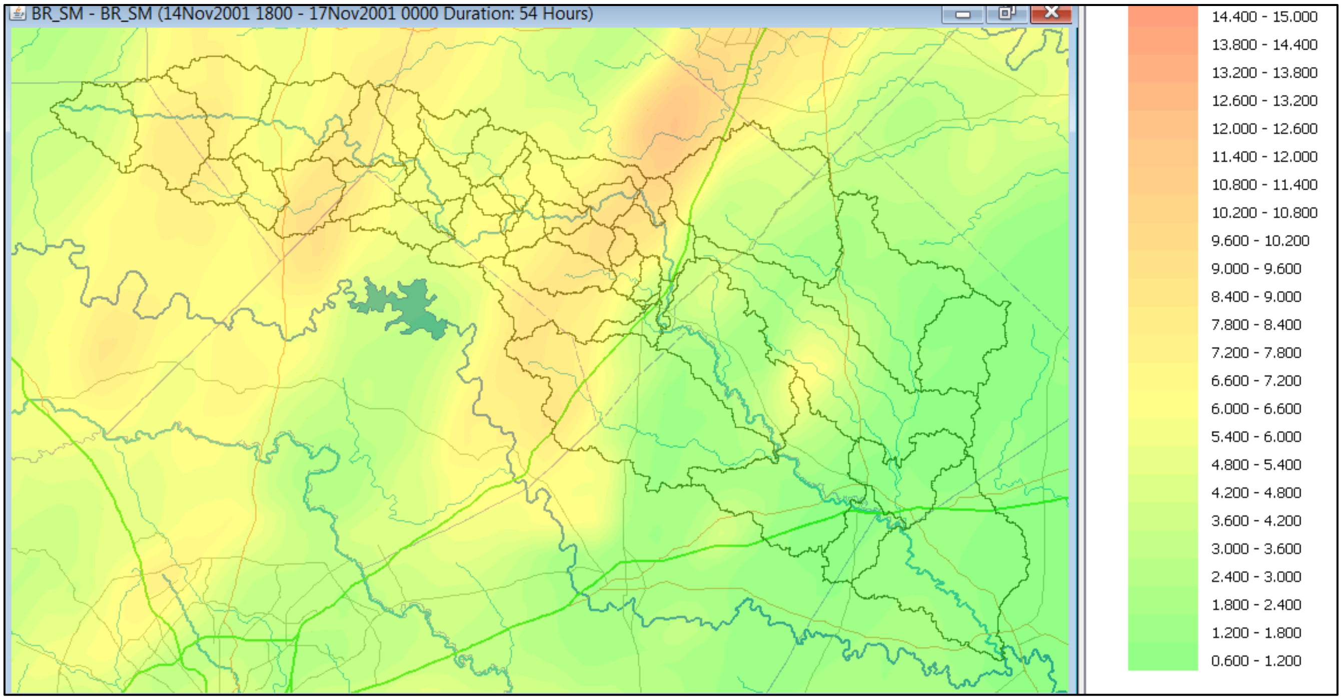

Figure 6.4: Rainfall Depths (inches) for the November 2001 Calibration Storm

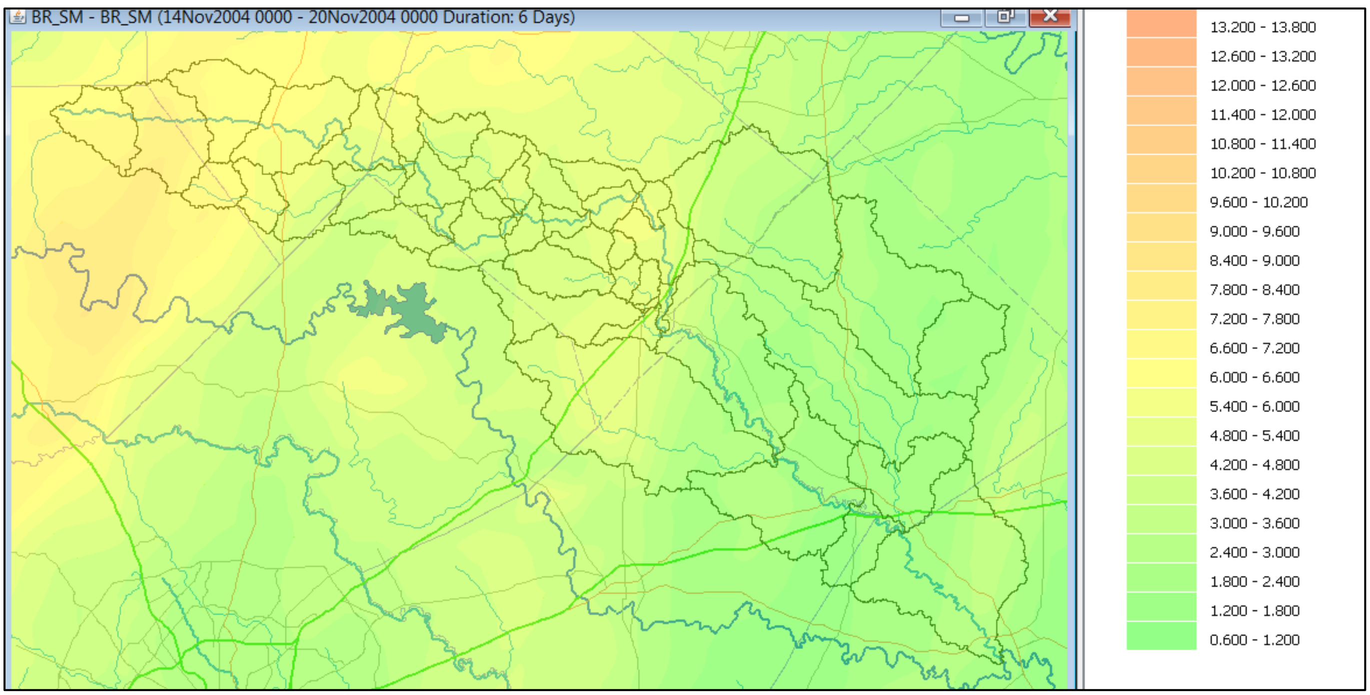

Figure 6.5: Rainfall Depths (inches) for the November 2004 Calibration Storm

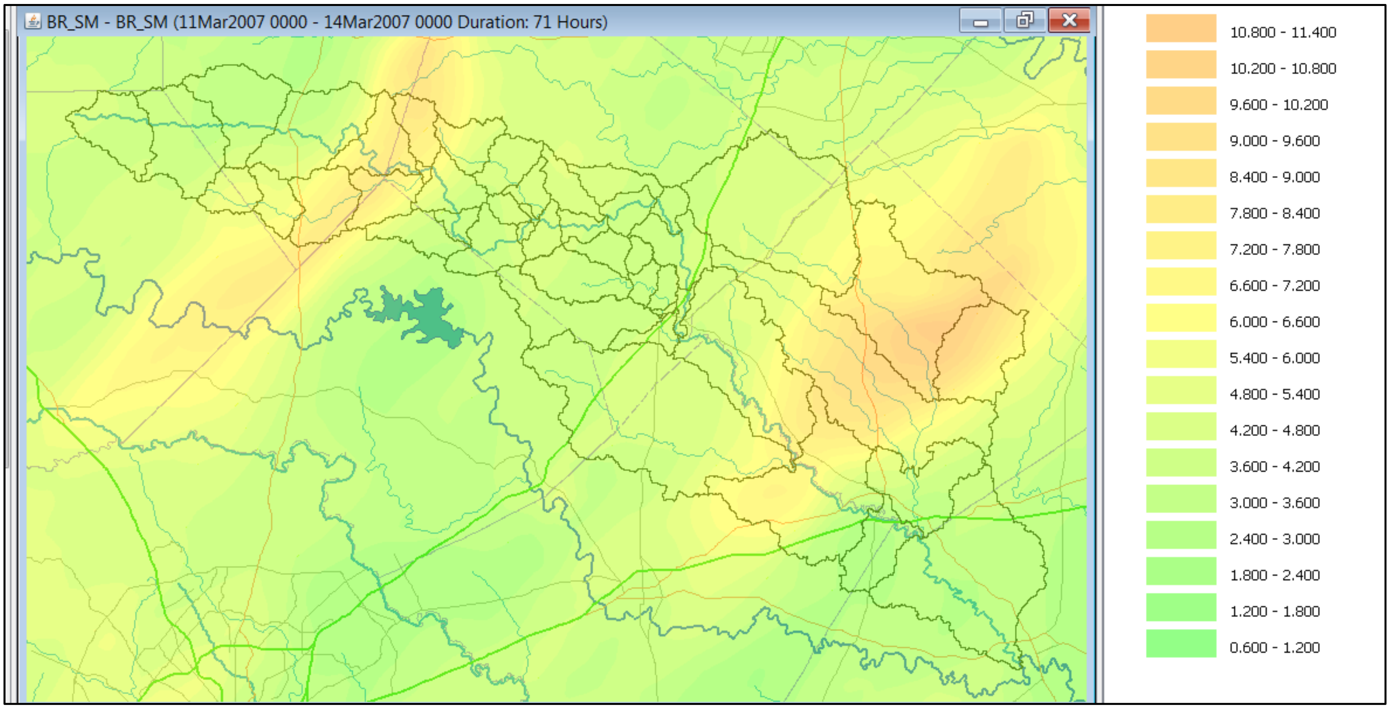

Figure 6.6: Rainfall Depths (inches) for the March 2007 Calibration Storm

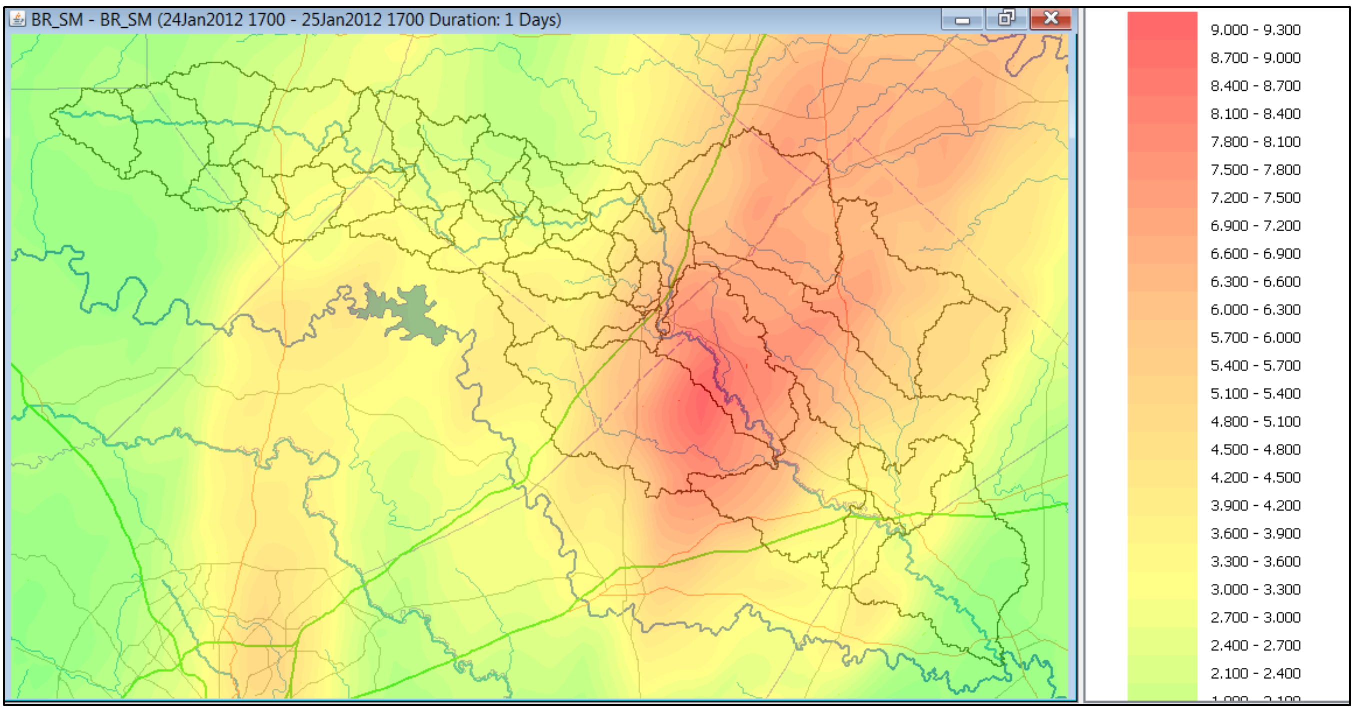

Figure 6.7: Rainfall Depths (inches) for the Jan 2012 Calibration Storm

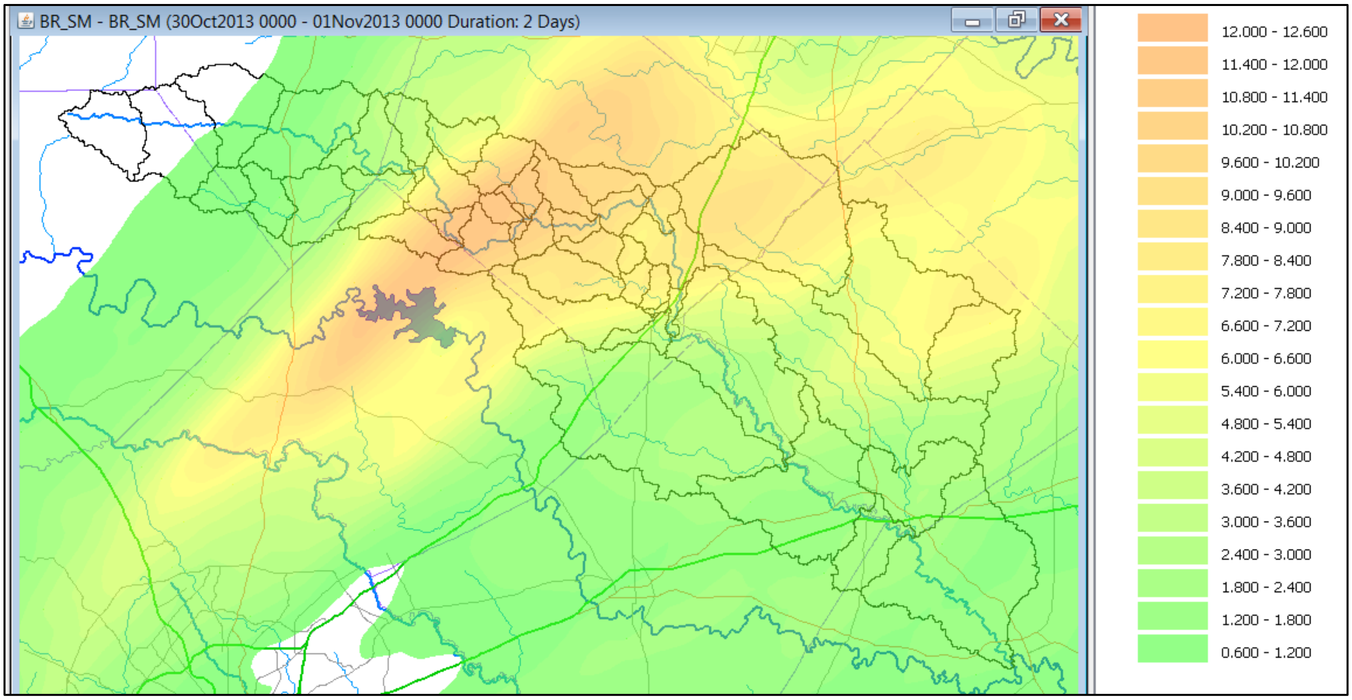

Figure 6.8: Rainfall Depths (inches) for the October 2013 Calibration Storm

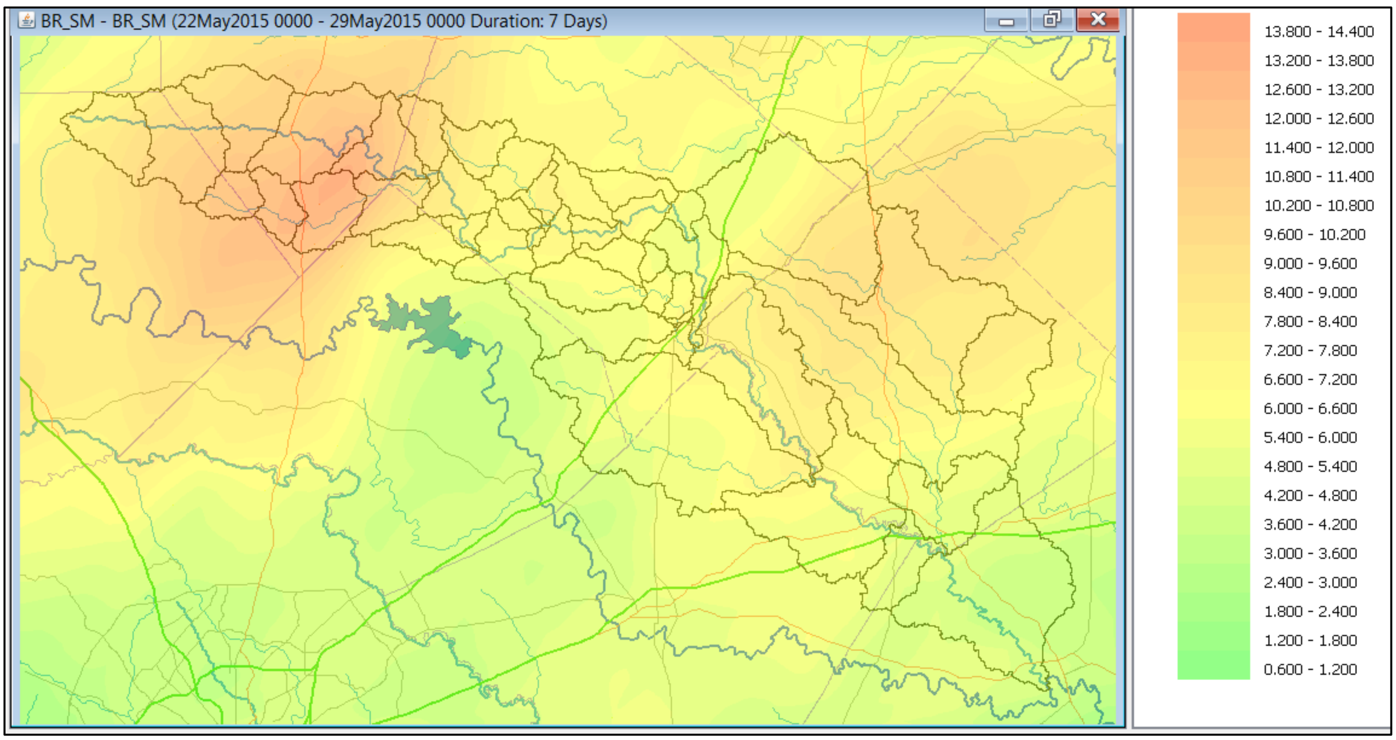

Figure 6.9: Rainfall Depths (inches) for the May 2015 Calibration Storm

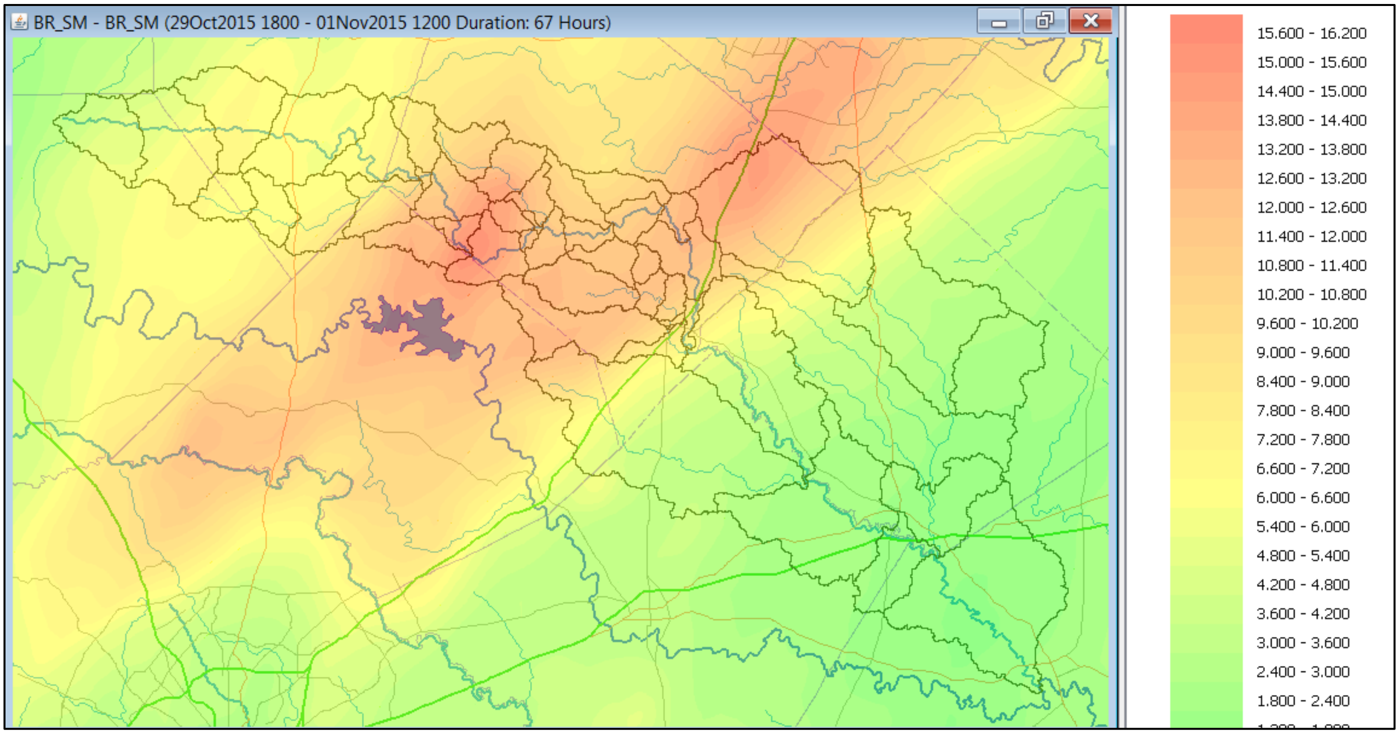

Figure 6.10: Rainfall Depths (inches) for the October 2015 Calibration Storm

Table 6.6 lists the stream flow gages that were calibrated for each event. Since the rain fell on different parts of the basin from one event to another, the calibration of each storm was focused on those areas of the basin that received the greatest and most intense rainfall. Calibration was also only performed when the USGS stream gages were recording for that event. For some events, one or more of the gages were not recording, but the peak flow was estimated by the USGS. These instances are listed as “Peak Only” in the table. This table shows that every gage was calibrated to at least three storms. Most of the gages were calibrated to between 5 and 7 storms.

Table 6.6: Calibrated Stream Gage Locations

	USGS Stream Gages that were used for Calibration					
Calibration Event	Blanco River at Wimberley	Blanco River near Kyle	San Marcos River at San Marcos	San Marcos River at Luling	Plum Creek at Lockhart	Plum Creek near Luling
Oct-1998	Yes	Yes	Peak Only	Yes	Yes	No
Nov-2001	Yes	Yes	No	No	No	No
Nov-2004	Yes	Peak Only	Peak Only	Yes	Yes	Peak Only
Mar-2007	Yes	Yes	Yes	No	No	No
Jan-2012	No	No	Yes	Yes	Yes	Yes
Oct-2013	Yes	Peak Only	No	No	No	No
May-2015	Yes	Peak Only	No	Yes	Yes	No
Oct-2015	Yes	Yes	No	Yes	Yes	Yes

6.4.1 Calibration Methodology

Following the initial parameter estimates, calibration simulations were made using observed hourly NEXRAD Stage III gridded precipitation data obtained from the West Gulf River Forecast Center (WGRFC). For each storm event, the model's calculated flow hydrographs were compared to the observed USGS stream flow data at the gages. The model's parameters were then adjusted to improve the match between the simulated and observed hydrographs for the observed events. Calibration was performed for the eight storm events listed in Table 6.5. Parameters that were adjusted during calibration included the subbasins' initial and constant loss rates, lag time, peaking coefficients, and baseflow parameters. The number of subreaches in the routing reaches were also adjusted in some cases.

Calibration was generally performed from upstream to downstream, with all subbasins upstream of a specific gage receiving uniform adjustments, unless specific rainfall or observed flow patterns necessitated adjusting subbasin parameters on an individual basis. Generally, subbasin parameters were adjusted in a consistent order: first baseflow parameters, then loss rates, and then lag times and peaking coefficients. Routing subreaches were the last to be adjusted. The methods of adjustment for each parameter are summarized in Table 6.7.

To the extent possible, effort was made to calibrate the model's results to the volume, timing, peak magnitude, and shape of the observed flow hydrograph. However, imperfections in the observed rainfall data and streamflow data did not always allow for a perfect match. For example, the gridded NEXRAD rainfall data from the National Weather Service was only available on an hourly basis. This meant that intense bursts of rain that occurred in 15-min or 30-min timespans might not be adequately represented in the hourly rainfall data. It also meant that even though the model was being run on a 15-min time step, the timing of the hydrographs could only be calibrated to the nearest hour. Likewise, the observed flow values at the gages are calculated indirectly from the observed stage and a limited number of flow measurements. While abundant flow measurements were usually available in the low flow range, the number and quality of USGS flow measurements were often very limited in the high flow range, leading to uncertainty in some of the observed flow hydrographs. In cases where all aspects of the observed flow hydrograph could not be calibrated perfectly, priority was given to matching the peak flow magnitude first, followed by the peak timing, which are the aspects of model calibration that are most relevant to the 1% annual chance (100-yr) flood estimation.

Table 6.7: HEC-HMS Calibration Approach

Parameter	Calibration Approach
Baseflow Parameters	First, the baseflow parameters were adjusted to match the observed flow rates at the start and end of each calibration event. The initial discharges for the subbasins upstream of a certain gage were adjusted uniformly up or down to match the initial observed discharge at that gage. Similarly, the recession constant was adjusted to match the slope of the recession limb of the observed hydrograph, and the ratio to peak was adjusted to match the observed discharge at the end of the calibration event. All baseflow parameters were adjusted uniformly for all subbasins upstream of a given gage with the only exception being subbasins that contained a spring. Subbasins containing springs were given higher baseflow parameters than the surrounding subbasins.
Initial Loss (in)	After adjusting the baseflow parameters, the initial and constant losses were adjusted to calibrate the total volume of the flood hydrograph. The initial loss was adjusted according to the antecedent soil moisture conditions at the beginning of each observed storm event. The initial loss was increased or decreased until the timing and volume of the initial runoff generally matched the observed arrival of the flow hydrograph at the nearest downstream gage. All subbasins that were upstream of each gage were generally adjusted uniformly, unless specific rainfall and observed flow patterns necessitated adjusting the subbasin initial losses on an individual basis.
Constant Loss Rate (in/hr)	After adjusting the baseflow parameters, the initial and constant losses were adjusted to calibrate the total volume of the flood hydrograph. The subbasins' constant loss rates were increased or decreased until the volume and magnitude of the simulated hydrographs generally matched the observed volume of the flow hydrograph at the nearest downstream gage. The combination of the adjusted baseflow and loss rate parameters led to the total calibrated volume at the gage.
Lag Time (hours)	After adjusting the loss rates, the Snyder's lag times were the next parameters to be adjusted upstream of an individual gage. The Snyder's lag times were adjusted to match the timing of the observed peak flow at the gage. Normally, all of the subbasin lag times upstream of an individual gage were adjusted uniformly and proportionally to one another, unless the magnitude or shape of the observed hydrograph necessitated making individual adjustments. Efforts were also made to ensure that the adjusted lag times still fell within a reasonable range, using the lag times corresponding to 0% sand and 100% sand in the Fort Worth District regional lag time equation as a guide.
Peaking Coefficient	Peaking coefficients were adjusted to match the general shape of the observed flow hydrograph as higher peaking coefficients produce steeper, narrower flood hydrographs, and lower peaking coefficients produce flatter, wider flood hydrographs. An attempt was made to use the same peaking coefficient for all subbasins with similar watershed characteristics. For example, steep, hilly subbasins were given a higher peaking coefficient, whereas flatter subbasins or subbasins with a lot of NRCS dams were given lower peaking coefficients. Efforts were also made to ensure that the adjusted peaking coefficients still fell within the typical range of 0.4 to 0.8. In most cases, peaking coefficients were adjusted once and left alone between subsequent events.
Routing Subreaches	The number of subreaches in the Modified Puls routing reaches were the final parameters to be adjusted if necessary. Adjustments to the number of subreaches in a given routing reach were made in order to match the amount of attenuation in the peak flow that occurred from the upstream end of a reach to the downstream gage.

6.4.2 Calibrated Parameters

The resulting calibrated subbasin and routing reach parameters that were adjusted for each storm event are shown in Tables 6.8 to 6.15.

Table 6.8: Calibrated Initial Losses (inches)

Subbasin Name	Initial	Oct 1998	Nov 2001	Nov 2004	Mar 2007	Jan 2012	Oct 2013	May 2015	Oct 2015
Blanco_S010	1	1	2	1.5	2	-	0.1	0.45	3
Blanco_S020	1	1	2	1.5	2.2	-	0.1	0.45	3
Blanco_S030	1	1	2	1.5	2	-	0.5	0.45	3
Blanco_S040	1	1.5	2	1	3	-	1	0.45	3
Blanco_S050	1	1.5	2	1	3	-	1.5	0.45	3
LittleBlanco_S010	1	1.5	2	0.5	3	-	1	0.45	4
LittleBlanco_S020	1	1.5	2	0.5	3	-	1	0.45	4
LittleBlanco_S030	1	1.5	2	0.5	3	-	1.5	0.45	4
LittleBlanco_S040	1	1.5	2	0.5	3	-	1.5	0.45	4
Blanco_S060	1	2	2	0.5	3	-	1.5	0.45	4
WanslowCr_BR_S010	1	2	2	1	3	-	1.5	0.45	4
Blanco_S070	1	2	2	1	3	-	4	0.6	5
Blanco_S080	1	2	2	1	2.5	-	3.5	0.6	5
CarpersCr_BR_S010	1	2	2	1	2.5	-	3.5	0.6	5
Blanco_S090	1	2	2	0.5	2.5	-	3.5	0.6	5
Blanco_S100	1	2	2	0.5	2.5	-	4	0.6	5
WilsonCr_BR_S010	1	2	2	0.5	2.5	-	4	0.6	5
Blanco_S110	1	2	2	0.5	2.5	-	4	0.6	5
CypressCr_BR_S010	1	2	2	2	2.8	-	2.5	0.8	5
CypressCr_BR_S020	1	2	2	2	2.8	-	3.5	0.8	5
CypressCr_BR_S030	1	2	2	2	2.8	-	3.5	0.8	5
Blanco_S120	1	2.5	2.5	2.5	2.5	-	4	0.4	0.8
Blanco_S130	1	2.5	2.5	2.5	2.5	-	4	0.4	0.8
LoneManCr_BR_S010	1	2.5	2.5	2.5	2.5	-	4	0.4	0.8
Blanco_S140	1	2.5	2.5	2.5	2.5	-	4	0.4	0.8
HalifaxCr_BR_S010	1	2	2.5	2.5	2.5	-	4	0.4	0.8
Blanco_S150	1	2	2.5	2.5	2.5	-	4	0.4	0.8
Blanco_S160	1	2	2.5	2.5	2.5	-	4	0.4	0.8
Blanco_S170	1	2.5	2.5	2.5	2.5	-	4	0.4	0.8
SinkCk_S010	1	1.0	-	1.4	0.8	-	-	0.1	4.5
SinkCk_S020	1	1.0	-	1.4	0.8	-	-	0.1	4.5
SinkCk_S030	1	1.0	-	1.4	0.8	-	-	0.1	4.5
SinkCk_S040	1	1.0	-	1.4	0.8	-	-	0.1	4.5
SanMarcos_S005	1	1.0	-	1.4	0.8	-	-	0.1	4.5
SanMarcos_S008	1	1.0	-	1.4	0.8	-	-	0.1	4.5
PurgatoryCr_S010	1	1.5	-	0.4	-	3.8	-	0.1	4.5
SanMarcos_S010	1	2.0	-	0.4	-	3.8	-	0.1	4.5
SanMarcos_S020	1	2.0	-	0.4	-	3.8	-	0.1	3.5
YorkCr_S010	1	3.0	-	0.6	-	4.7	-	0.4	4
SanMarcos_S030	1	2.5	-	1	-	3.8	-	0.1	1.5
SanMarcos_S040	1	2.0	-	1	-	3.8	-	0.1	1
PlumCr_S010	1	4.0	-	0.6	-	3	-	0.1	5
PlumCr_S020	1	1.5	-	0.2	-	3	-	0.1	4
TenneyCr_S010	1	1.5	-	0.2	-	3	-	0.1	4
PlumCr_S030	1	1.5	-	0.2	-	3	-	0.1	4
PlumCr_S040	1	1.5	-	0.2	-	4	-	0.1	4
SanMarcos_S050	1	3.0	-	0.2	-	4.5	-	0.1	4.5

Table 6.9: Calibrated Constant Losses (inches per hour)

Subbasin Name	Initial	Oct 1998	Nov 2001	Nov 2004	Mar 2007	Jan 2012	Oct 2013	May 2015	Oct 2015
Blanco_S010	0.15	0.6	0.06	0.2	0.2	-	0.03	0.04	0.5
Blanco_S020	0.15	0.6	0.06	0.2	0.2	-	0.03	0.04	0.5
Blanco_S030	0.14	0.5	0.06	0.2	0.25	-	0.03	0.04	0.5
Blanco_S040	0.14	0.5	0.06	0.14	0.25	-	0.03	0.04	0.5
Blanco_S050	0.14	0.5	0.06	0.14	0.25	-	0.03	0.04	0.5
LittleBlanco_S010	0.15	0.4	0.06	0.14	0.25	-	0.03	0.04	0.5
LittleBlanco_S020	0.15	0.4	0.06	0.14	0.25	-	0.03	0.04	0.5
LittleBlanco_S030	0.14	0.4	0.06	0.14	0.25	-	0.03	0.04	0.5
LittleBlanco_S040	0.15	0.4	0.06	0.14	0.25	-	0.03	0.04	0.5
Blanco_S060	0.15	0.4	0.06	0.14	0.25	-	0.03	0.04	0.5
WanslowCr_BR_S010	0.15	0.4	0.06	0.1	0.25	-	0.03	0.04	0.5
Blanco_S070	0.15	0.4	0.08	0.1	0.25	-	0.03	0.04	0.5
Blanco_S080	0.15	0.5	0.08	0.1	0.25	-	0.03	0.04	0.5
CarpersCr_BR_S010	0.15	0.5	0.08	0.1	0.25	-	0.03	0.04	0.5
Blanco_S090	0.15	0.5	0.08	0.1	0.25	-	0.02	0.04	0.5
Blanco_S100	0.15	0.5	0.08	0.1	0.25	-	0.02	0.04	0.5
WilsonCr_BR_S010	0.15	0.5	0.08	0.1	0.25	-	0.02	0.04	0.5
Blanco_S110	0.15	0.5	0.08	0.1	0.25	-	0.02	0.04	0.5
CypressCr_BR_S010	0.15	0.5	0.08	0.1	0.25	-	0.02	0.04	0.5
CypressCr_BR_S020	0.15	0.5	0.08	0.1	0.25	-	0.02	0.04	0.5
CypressCr_BR_S030	0.15	0.5	0.08	0.1	0.25	-	0.02	0.04	0.5
Blanco_S120	0.15	0.5	0.15	0.2	0.17	-	0.15	0.01	0.12
Blanco_S130	0.15	0.5	0.15	0.2	0.17	-	0.15	0.01	0.12
LoneManCr_BR_S010	0.15	0.5	0.15	0.2	0.17	-	0.15	0.01	0.12
Blanco_S140	0.15	0.5	0.15	0.2	0.17	-	0.15	0.01	0.12
HalifaxCr_BR_S010	0.14	0.4	0.15	0.2	0.17	-	0.15	0.01	0.12
Blanco_S150	0.14	0.4	0.15	0.2	0.17	-	0.15	0.01	0.12
Blanco_S160	0.14	0.4	0.15	0.2	0.17	-	0.15	0.01	0.12
Blanco_S170	0.15	0.5	0.15	0.2	0.17	-	0.15	0.01	0.12
SinkCk_S010	0.12	0.1	-	0.14	0.33	-	-	0.38	0.31
SinkCk_S020	0.12	0.1	-	0.14	0.33	-	-	0.38	0.31
SinkCk_S030	0.12	0.1	-	0.14	0.33	-	-	0.38	0.31
SinkCk_S040	0.12	0.1	-	0.14	0.33	-	-	0.38	0.31
SanMarcos_S005	0.12	0.1	-	0.14	0.33	-	-	0.38	0.31
SanMarcos_S008	0.12	0.1	-	0.14	0.33	-	-	0.38	0.31
PurgatoryCr_S010	0.12	0.1	-	0.01	-	0.14	-	0.38	0.31
SanMarcos_S010	0.13	0.1	-	0.01	-	0.14	-	0.38	0.31
SanMarcos_S020	0.13	0.1	-	0.01	-	0.14	-	0.38	0.1
YorkCr_S010	0.12	0.2	-	0.04	-	0.2	-	0.45	0.15
SanMarcos_S030	0.13	0.1	-	0.01	-	0.14	-	0.4	0.1
SanMarcos_S040	0.14	0.1	-	0.01	-	0.14	-	0.4	0.1
PlumCr_S010	0.12	0.0	-	0.13	-	0.4	-	0.37	0.04
PlumCr_S020	0.13	0.1	-	0.06	-	0.42	-	0.38	0.04
TenneyCr_S010	0.14	0.1	-	0.07	-	0.45	-	0.41	0.04
PlumCr_S030	0.13	0.1	-	0.06	-	0.42	-	0.38	0.04
PlumCr_S040	0.13	0.1	-	0.01	-	0.04	-	0.4	0.04
SanMarcos_S050	0.14	0.3	-	0.01	-	0.35	-	0.43	0.35

Table 6.10: Calibrated Snyder's Lag Time (hours)

Subbasin Name	Initial	Oct 1998	Nov 2001	Nov 2004	Mar 2007	Jan 2012	Oct 2013	May 2015	Oct 2015
Blanco_S010	3.2	2.0	2	2.7	2.2	-	2	2	2
Blanco_S020	3.9	2.4	2.4	3.3	2.8	-	2.4	2.4	2.4
Blanco_S030	2.9	1.9	1.9	2.6	2.1	-	1.9	1.9	1.9
Blanco_S040	5.2	3.5	3.5	4.8	3.7	-	3.5	3.5	3.5
Blanco_S050	4.9	3.4	3.4	4.6	3.1	-	3.4	3.4	3.4
LittleBlanco_S010	2.2	2.2	2.2	2.2	1.2	-	2.2	2.2	1.7
LittleBlanco_S020	2.6	2.4	2.4	2.6	1.5	-	2.6	2.4	2.1
LittleBlanco_S030	2.9	2.8	2.8	2.9	1.8	-	2.9	2.8	2.5
LittleBlanco_S040	4.2	3.7	3.7	4.2	2.3	-	3.7	3.7	3.2
Blanco_S060	0.9	0.8	0.6	0.8	0.6	-	0.8	0.6	0.6
WanslowCr_BR_S010	3.2	3.0	2.6	3	1.9	-	1.9	3	3.2
Blanco_S070	2.9	2.8	2.3	2.8	1.7	-	1.7	2.8	1.7
Blanco_S080	2.7	2.6	2.2	2.6	1.6	-	1.6	2.6	1.6
CarpersCr_BR_S010	4.4	4.1	3.5	4.1	3.1	-	2.4	4.1	2.4
Blanco_S090	3.1	3.0	2.5	3	2.2	-	1.8	3	1.8
Blanco_S100	1.2	1.1	0.9	1.1	0.8	-	0.7	1.1	0.7
WilsonCr_BR_S010	2.6	2.4	2	2.4	1.8	-	1.5	2.4	1.5
Blanco_S110	1.0	1.0	0.8	1	0.7	-	0.6	1	0.6
CypressCr_BR_S010	2.7	2.7	2.2	2.7	2.2	-	1.7	2.2	1.7
CypressCr_BR_S020	2.5	2.5	1.9	2.5	1.9	-	1.6	1.9	1.6
CypressCr_BR_S030	3.2	2.7	2.2	2.7	2.2	-	1.7	2.2	1.7
Blanco_S120	2.1	1.7	1.7	2.1	1.7	-	2.1	2.2	1.7
Blanco_S130	2.9	2.3	2.3	2.9	2.3	-	2.9	3	2.3
LoneManCr_BR_S010	4.8	3.0	3	4.8	3	-	4.8	4.8	3.0
Blanco_S140	2.9	2.3	2.3	2.9	2.3	-	2.9	3	2.3
HalifaxCr_BR_S010	4.6	3.3	3.3	4.6	3.3	-	4.6	5.2	3.3
Blanco_S150	2.8	2.4	2.4	2.8	2.4	-	2.8	3.2	2.4
Blanco_S160	3.6	3.3	3.3	3.3	3.3	-	3.6	3.6	3.3
Blanco_S170	3.9	2.5	2.5	2.5	2.5	-	2.5	2.5	2.5
SinkCk_S010	4.4	4.4	-	4.4	4.4	-	-	-	4.4
SinkCk_S020	3.4	3.4	-	3.4	3.4	-	-	-	3.4
SinkCk_S030	1.1	1.9	-	1.6	1.6	-	-	-	1.9
SinkCk_S040	1.4	2.3	-	2	2	-	-	-	2.3
SanMarcos_S005	1.5	2.6	-	2.2	2.2	-	-	-	2.6
SanMarcos_S008	0.8	1.4	-	1.2	1.2	-	-	-	1.4
PurgatoryCr_S010	8.5	5.5	-	5.5	-	8.5	-	8.5	5.5
SanMarcos_S010	1.9	1.9	-	1.9	-	1.9	-	1.9	1.9
SanMarcos_S020	8.6	6.8	-	7.5	-	6.75	-	6.75	6.75
YorkCr_S010	6.5	8.5	-	8.5	-	8.5	-	8.5	8.5
SanMarcos_S030	6.9	7.5	-	9	-	7.5	-	7.5	7.5
SanMarcos_S040	5.0	5.0	-	5	-	5	-	5	5
PlumCr_S010	12.1	6.1	-	12.1	-	3.6	-	3.6	6.1
PlumCr_S020	5.3	5.3	-	5.3	-	6.9	-	8	5.3
TenneyCr_S010	4.0	4.0	-	4	-	5.2	-	6	4
PlumCr_S030	6.8	17.0	-	17	-	8.8	-	10.2	6.8
PlumCr_S040	4.6	4.6	-	4.6	-	4.6	-	4.6	4.6
SanMarcos_S050	13.0	13.0	-	13	-	13	-	13	13

Table 6.11: Calibrated Snyder's Peaking Coefficient

Subbasin Name	Initial	Oct 1998	Nov 2001	Nov 2004	Mar 2007	Jan 2012	Oct 2013	May 2015	Oct 2015
Blanco_S010	0.72	0.78	0.78	0.78	0.78	-	0.78	0.78	0.78
Blanco_S020	0.72	0.78	0.78	0.78	0.78	-	0.78	0.78	0.78
Blanco_S030	0.72	0.78	0.78	0.78	0.78	-	0.78	0.78	0.78
Blanco_S040	0.72	0.78	0.78	0.78	0.78	-	0.78	0.78	0.78
Blanco_S050	0.72	0.78	0.78	0.78	0.78	-	0.78	0.78	0.78
LittleBlanco_S010	0.72	0.78	0.78	0.78	0.78	-	0.78	0.78	0.78
LittleBlanco_S020	0.72	0.78	0.78	0.78	0.78	-	0.78	0.78	0.78
LittleBlanco_S030	0.72	0.78	0.78	0.78	0.78	-	0.78	0.78	0.78
LittleBlanco_S040	0.72	0.78	0.78	0.78	0.78	-	0.78	0.78	0.78
Blanco_S060	0.72	0.78	0.78	0.78	0.78	-	0.78	0.78	0.78
WanslowCr_BR_S010	0.72	0.78	0.78	0.78	0.78	-	0.78	0.78	0.78
Blanco_S070	0.72	0.78	0.78	0.78	0.78	-	0.78	0.78	0.78
Blanco_S080	0.72	0.78	0.78	0.78	0.78	-	0.78	0.78	0.78
CarpersCr_BR_S010	0.72	0.78	0.78	0.78	0.78	-	0.78	0.78	0.78
Blanco_S090	0.72	0.78	0.78	0.78	0.78	-	0.78	0.78	0.78
Blanco_S100	0.72	0.78	0.78	0.78	0.78	-	0.78	0.78	0.78
WilsonCr_BR_S010	0.72	0.78	0.78	0.78	0.78	-	0.78	0.78	0.78
Blanco_S110	0.72	0.78	0.78	0.78	0.78	-	0.78	0.78	0.78
CypressCr_BR_S010	0.72	0.78	0.78	0.78	0.78	-	0.78	0.78	0.78
CypressCr_BR_S020	0.72	0.78	0.78	0.78	0.78	-	0.78	0.78	0.78
CypressCr_BR_S030	0.72	0.78	0.78	0.78	0.78	-	0.78	0.78	0.78
Blanco_S120	0.72	0.70	0.72	0.72	0.72	-	0.7	0.72	0.72
Blanco_S130	0.72	0.70	0.72	0.72	0.72	-	0.7	0.72	0.72
LoneManCr_BR_S010	0.72	0.70	0.72	0.72	0.72	-	0.7	0.72	0.72
Blanco_S140	0.72	0.70	0.72	0.72	0.72	-	0.7	0.72	0.72
HalifaxCr_BR_S010	0.72	0.70	0.72	0.72	0.72	-	0.7	0.72	0.72
Blanco_S150	0.72	0.70	0.72	0.72	0.72	-	0.7	0.72	0.72
Blanco_S160	0.72	0.70	0.72	0.72	0.72	-	0.7	0.72	0.72
Blanco_S170	0.72	0.70	0.75	0.75	0.75	-	0.7	0.75	0.75
SinkCk_S010	0.7813	0.8	-	0.7813	0.7813	0.7813	-	-	-
SinkCk_S020	0.7813	0.8	-	0.7813	0.7813	0.7813	-	-	-
SinkCk_S030	0.7813	0.8	-	0.7813	0.7813	0.7813	-	-	-
SinkCk_S040	0.7813	0.8	-	0.7813	0.7813	0.7	-	-	-
SanMarcos_S005	0.7813	0.8	-	0.7813	0.7813	0.7813	-	-	-
SanMarcos_S008	0.7813	0.8	-	0.7813	0.7813	0.7813	-	-	-
PurgatoryCr_S010	0.7813	0.8	-	0.7813	-	0.4688	-	0.7813	0.7813
SanMarcos_S010	0.7813	0.8	-	0.75	-	0.7813	-	0.75	0.75
SanMarcos_S020	0.7813	0.8	-	0.75	-	0.7813	-	0.75	0.75
YorkCr_S010	0.7813	0.7	-	0.7	-	0.7813	-	0.65	0.65
SanMarcos_S030	0.7813	0.8	-	0.75	-	0.7813	-	0.75	0.75
SanMarcos_S040	0.7813	0.8	-	0.75	-	0.7813	-	0.75	0.75
PlumCr_S010	0.7813	0.6	-	0.7813	-	-	-	0.4688	0.6485
PlumCr_S020	0.7813	0.8	-	0.7813	-	-	-	0.7813	0.7813
TenneyCr_S010	0.7813	0.8	-	0.7813	-	-	-	0.7813	0.7813
PlumCr_S030	0.7813	0.8	-	0.7813	-	-	-	0.7813	0.7813
PlumCr_S040	0.7813	0.8	-	0.7813	-	-	-	0.7813	0.7813
SanMarcos_S050	0.7813	0.8	-	0.7813	-	-	-	0.7813	0.7813

Table 6.12: Calibrated Initial Baseflow (cfs per sq mi)

Subbasin Name	Initial	Oct 1998	Nov 2001	Nov 2004	Mar 2007	Jan 2012	Oct 2013	May 2015	Oct 2015
Blanco_S010	0.2	0.17	0.20	0.65	0.04	-	0.06	1.25	0.13
Blanco_S020	0.2	0.17	0.20	0.65	0.04	-	0.06	1.25	0.13
Blanco_S030	0.2	0.17	0.20	0.65	0.04	-	0.06	1.25	0.13
Blanco_S040	0.2	0.17	0.20	0.65	0.04	-	0.06	1.25	0.13
Blanco_S050	0.2	0.17	0.20	0.65	0.04	-	0.06	1.25	0.13
LittleBlanco_S010	0.2	0.17	0.20	0.65	0.04	-	0.06	1.25	0.13
LittleBlanco_S020	0.2	0.17	0.20	0.65	0.04	-	0.06	1.25	0.13
LittleBlanco_S030	0.2	0.17	0.20	0.65	0.04	-	0.06	1.25	0.13
LittleBlanco_S040	0.2	0.17	0.20	0.65	0.04	-	0.06	1.25	0.13
Blanco_S060	0.2	0.17	0.20	0.65	0.04	-	0.06	1.25	0.15
WanslowCr_BR_S010	0.2	0.17	0.20	0.65	0.04	-	0.06	1.25	0.15
Blanco_S070	0.2	0.17	0.20	0.65	0.04	-	0.06	1.25	0.15
Blanco_S080	0.2	0.17	0.20	0.65	0.04	-	0.06	1.25	0.15
CarpersCr_BR_S010	0.2	0.17	0.20	0.65	0.04	-	0.06	1.25	0.15
Blanco_S090	0.2	0.17	0.20	0.65	0.04	-	0.06	1.25	0.15
Blanco_S100	0.2	0.17	0.20	0.65	0.04	-	0.06	1.25	0.15
WilsonCr_BR_S010	0.2	0.17	0.20	0.65	0.04	-	0.06	1.25	0.15
Blanco_S110	0.2	0.17	0.20	0.65	0.04	-	0.06	1.25	0.15
CypressCr_BR_S010	0.2	0.17	0.20	0.65	0.04	-	0.06	1.25	0.15
CypressCr_BR_S020	0.2	0.75	0.80	0.9	0.6	-	0.7	2.5	0.8
CypressCr_BR_S030	0.2	0.17	0.10	0.65	0.04	-	0.06	1.5	0.15
Blanco_S120	0.2	0.10	0.10	0.05	0.04	-	0.1	1.5	0.1
Blanco_S130	0.2	0.10	0.10	0.05	0.04	-	0.1	1.5	0.1
LoneManCr_BR_S010	0.2	0.10	0.10	0.05	0.04	-	0.1	1.5	0.1
Blanco_S140	0.2	0.10	0.10	0.05	0.04	-	0.1	1.5	0.1
HalifaxCr_BR_S010	0.2	0.10	0.10	0.05	0.04	-	0.1	1.5	0.1
Blanco_S150	0.2	0.10	0.10	0.05	0.04	-	0.1	1.5	0.1
Blanco_S160	0.2	0.10	0.10	0.05	0.04	-	0.1	1	0.1
Blanco_S170	0.2	0.10	0.10	0.05	0.04	-	0.1	1	0.1
SinkCk_S010	0.3	0.3	-	0.3	0.3	0.3	-	0.3	0.3
SinkCk_S020	0.3	0.3	-	0.3	0.3	0.3	-	0.3	0.3
SinkCk_S030	0.3	0.3	-	0.3	0.3	0.3	-	0.3	0.3
SinkCk_S040	0.3	0.3	-	0.3	0.3	0.3	-	0.3	0.3
SanMarcos_S005	0.3	0.3	-	0.3	0.3	0.3	-	0.3	0.3
SanMarcos_S008	0.3	4.0	-	4.8	-	2	-	4	4
PurgatoryCr_S010	0.3	0.3	-	4	-	0.2	-	0.6	0.3
SanMarcos_S010	0.3	0.3	-	4	-	0.2	-	0.6	0.2
SanMarcos_S020	0.3	0.3	-	4	-	0.2	-	0.6	0.2
YorkCr_S010	0.3	0.3	-	4	-	0.2	-	0.6	0.3
SanMarcos_S030	0.3	0.3	-	4	-	0.2	-	0.6	0.2
SanMarcos_S040	0.3	0.3	-	4	-	0.2	-	0.3	0.2
PlumCr_S010	0.3	0.0	-	4	-	0.01	-	3	0.01
PlumCr_S020	0.3	0.0	-	0.01	-	0.01	-	0.01	0.01
TenneyCr_S010	0.3	0.0	-	0.01	-	0.01	-	0.01	0.01
PlumCr_S030	0.3	0.0	-	0.01	-	0.01	-	0.01	0.01
PlumCr_S040	0.3	0.3	-	0.3	-	0.3	-	0.3	0.3
SanMarcos_S050	0.3	0.3	-	0.3	-	0.3	-	0.3	0.3

Table 6.13: Calibrated Baseflow Recession Constant

Subbasin Name	Initial	Oct 1998	Nov 2001	Nov 2004	Mar 2007	Jan 2012	Oct 2013	May 2015	Oct 2015
Blanco_S010	0.92	0.89	0.80	0.8	0.8	-	0.7	0.8	0.7
Blanco_S020	0.92	0.89	0.80	0.8	0.8	-	0.7	0.8	0.7
Blanco_S030	0.92	0.89	0.80	0.8	0.8	-	0.7	0.8	0.7
Blanco_S040	0.92	0.89	0.80	0.8	0.8	-	0.7	0.8	0.7
Blanco_S050	0.92	0.89	0.80	0.8	0.8	-	0.7	0.8	0.7
LittleBlanco_S010	0.92	0.89	0.80	0.8	0.8	-	0.7	0.8	0.7
LittleBlanco_S020	0.92	0.89	0.80	0.8	0.8	-	0.7	0.8	0.7
LittleBlanco_S030	0.92	0.89	0.80	0.8	0.8	-	0.7	0.8	0.7
LittleBlanco_S040	0.92	0.89	0.80	0.8	0.8	-	0.7	0.8	0.7
Blanco_S060	0.92	0.89	0.80	0.8	0.8	-	0.7	0.8	0.7
WanslowCr_BR_S010	0.92	0.89	0.80	0.8	0.8	-	0.7	0.8	0.7
Blanco_S070	0.92	0.89	0.80	0.8	0.8	-	0.7	0.8	0.7
Blanco_S080	0.92	0.89	0.80	0.8	0.8	-	0.7	0.8	0.7
CarpersCr_BR_S010	0.92	0.89	0.80	0.8	0.8	-	0.7	0.8	0.7
Blanco_S090	0.92	0.89	0.80	0.8	0.8	-	0.7	0.8	0.7
Blanco_S100	0.92	0.89	0.80	0.8	0.8	-	0.7	0.8	0.7
WilsonCr_BR_S010	0.92	0.89	0.80	0.8	0.8	-	0.7	0.8	0.7
Blanco_S110	0.92	0.89	0.80	0.8	0.8	-	0.7	0.8	0.7
CypressCr_BR_S010	0.92	0.89	0.80	0.8	0.8	-	0.7	0.8	0.7
CypressCr_BR_S020	0.92	0.95	0.95	0.95	0.95	-	0.95	0.95	0.95
CypressCr_BR_S030	0.92	0.89	0.80	0.8	0.8	-	0.7	0.8	0.7
Blanco_S120	0.89	0.89	0.80	0.8	0.8	-	0.89	0.8	0.89
Blanco_S130	0.89	0.89	0.80	0.8	0.8	-	0.89	0.8	0.89
LoneManCr_BR_S010	0.89	0.89	0.80	0.8	0.8	-	0.89	0.8	0.89
Blanco_S140	0.89	0.89	0.80	0.8	0.8	-	0.89	0.8	0.89
HalifaxCr_BR_S010	0.89	0.89	0.80	0.8	0.8	-	0.89	0.8	0.89
Blanco_S150	0.89	0.89	0.80	0.8	0.8	-	0.89	0.8	0.89
Blanco_S160	0.89	0.89	0.80	0.8	0.8	-	0.89	0.8	0.89
Blanco_S170	0.89	0.89	0.80	0.8	0.8	-	0.89	0.8	0.89
SinkCk_S010	0.89	0.89	-	0.89	0.89	0.89	-	0.89	0.89
SinkCk_S020	0.89	0.89	-	0.89	0.89	0.89	-	0.89	0.89
SinkCk_S030	0.89	0.89	-	0.89	0.89	0.89	-	0.89	0.89
SinkCk_S040	0.89	0.89	-	0.89	0.89	0.89	-	0.89	0.89
SanMarcos_S005	0.89	0.89	-	0.89	0.89	0.89	-	0.89	0.89
SanMarcos_S008	0.89	0.99	-	0.99	-	0.99	-	0.99	0.99
PurgatoryCr_S010	0.89	0.75	-	0.8	-	0.8	-	0.8	0.8
SanMarcos_S010	0.89	0.75	-	0.8	-	0.8	-	0.8	0.8
SanMarcos_S020	0.89	0.75	-	0.8	-	0.8	-	0.8	0.8
YorkCr_S010	0.79	0.85	-	0.85	-	0.85	-	0.85	0.85
SanMarcos_S030	0.89	0.75	-	0.8	-	0.8	-	0.8	0.8
SanMarcos_S040	0.89	0.75	-	0.8	-	0.8	-	0.8	0.8
PlumCr_S010	0.79	0.80	-	0.8	-	0.8	-	0.8	0.8
PlumCr_S020	0.79	0.50	-	0.5	-	0.5	-	0.5	0.5
TenneyCr_S010	0.79	0.50	-	0.5	-	0.5	-	0.5	0.5
PlumCr_S030	0.79	0.50	-	0.5	-	0.5	-	0.5	0.5
PlumCr_S040	0.79	0.79	-	0.79	-	0.79	-	0.79	0.79
SanMarcos_S050	0.89	0.89	-	0.89	-	0.89	-	0.89	0.89

Table 6.14: Calibrated Baseflow Ratio to Peak

Subbasin Name	Initial	Oct 1998	Nov 2001	Nov 2004	Mar 2007	Jan 2012	Oct 2013	May 2015	Oct 2015
Blanco_S010	0.03	0.015	0.015	0.05	0.008	-	0.002	0.01	0.001
Blanco_S020	0.03	0.015	0.015	0.05	0.008	-	0.002	0.01	0.001
Blanco_S030	0.03	0.015	0.015	0.05	0.008	-	0.002	0.01	0.001
Blanco_S040	0.03	0.015	0.015	0.05	0.008	-	0.002	0.01	0.001
Blanco_S050	0.03	0.015	0.015	0.05	0.008	-	0.002	0.01	0.001
LittleBlanco_S010	0.03	0.015	0.015	0.05	0.008	-	0.002	0.01	0.001
LittleBlanco_S020	0.03	0.015	0.015	0.05	0.008	-	0.002	0.01	0.001
LittleBlanco_S030	0.03	0.015	0.015	0.05	0.008	-	0.002	0.01	0.001
LittleBlanco_S040	0.03	0.015	0.015	0.05	0.008	-	0.002	0.01	0.001
Blanco_S060	0.03	0.015	0.015	0.05	0.008	-	0.002	0.01	0.001
WanslowCr_BR_S010	0.03	0.015	0.015	0.05	0.008	-	0.002	0.01	0.001
Blanco_S070	0.03	0.015	0.015	0.05	0.008	-	0.002	0.01	0.001
Blanco_S080	0.03	0.015	0.015	0.05	0.008	-	0.002	0.01	0.001
CarpersCr_BR_S010	0.03	0.015	0.015	0.05	0.008	-	0.002	0.01	0.001
Blanco_S090	0.03	0.015	0.015	0.05	0.008	-	0.002	0.01	0.001
Blanco_S100	0.03	0.015	0.015	0.05	0.008	-	0.002	0.01	0.001
WilsonCr_BR_S010	0.03	0.015	0.015	0.05	0.008	-	0.002	0.01	0.001
Blanco_S110	0.03	0.015	0.015	0.05	0.008	-	0.002	0.01	0.001
CypressCr_BR_S010	0.03	0.015	0.015	0.05	0.008	-	0.002	0.01	0.001
CypressCr_BR_S020	0.03	0.030	0.030	0.07	0.03	-	0.03	0.03	0.005
CypressCr_BR_S030	0.03	0.015	0.015	0.05	0.007	-	0.002	0.01	0.001
Blanco_S120	0.03	0.015	0.015	0.002	0.007	-	0.002	0.02	0.002
Blanco_S130	0.03	0.015	0.015	0.002	0.007	-	0.002	0.02	0.002
LoneManCr_BR_S010	0.03	0.015	0.015	0.002	0.007	-	0.002	0.02	0.002
Blanco_S140	0.03	0.015	0.015	0.002	0.007	-	0.002	0.02	0.002
HalifaxCr_BR_S010	0.03	0.015	0.015	0.002	0.007	-	0.002	0.02	0.002
Blanco_S150	0.02	0.015	0.015	0.002	0.007	-	0.002	0.02	0.002
Blanco_S160	0.02	0.015	0.015	0.002	0.007	-	0.002	0.01	0.002
Blanco_S170	0.02	0.015	0.015	0.002	0.007	-	0.002	0.01	0.002
SinkCk_S010	0.05	0.03	-	0.03	0.03	0.03	-	0.03	0.03
SinkCk_S020	0.05	0.03	-	0.03	0.03	0.03	-	0.03	0.03
SinkCk_S030	0.05	0.03	-	0.03	0.03	0.03	-	0.03	0.03
SinkCk_S040	0.05	0.03	-	0.03	0.03	0.03	-	0.03	0.03
SanMarcos_S005	0.05	0.03	-	0.03	0.03	0.03	-	0.03	0.03
SanMarcos_S008	0.05	0.03	-	0.14	-	0.2	-	0.07	0.03
PurgatoryCr_S010	0.05	0.01	-	0.02	-	0.01	-	0.02	0.02
SanMarcos_S010	0.05	0.01	-	0.02	-	0.01	-	0.02	0.02
SanMarcos_S020	0.05	0.01	-	0.02	-	0.01	-	0.02	0.02
YorkCr_S010	0.1	0.03	-	0.03	-	0.03	-	0.03	0.03
SanMarcos_S030	0.05	0.01	-	0.02	-	0.01	-	0.02	0.02
SanMarcos_S040	0.05	0.01	-	0.02	-	0.01	-	0.02	0.02
PlumCr_S010	0.1	0.05	-	0.15	-	0.05	-	0.05	0.05
PlumCr_S020	0.1	0.10	-	0.1	-	0.1	-	0.1	0.1
TenneyCr_S010	0.1	0.10	-	0.1	-	0.1	-	0.1	0.1
PlumCr_S030	0.1	0.10	-	0.1	-	0.1	-	0.1	0.1
PlumCr_S040	0.1	0.10	-	0.1	-	0.1	-	0.1	0.1
SanMarcos_S050	0.05	0.05	-	0.05	-	0.05	-	0.05	0.05

Table 6.15: Calibrated Routing Reach Modified Puls Subreaches

Reach Name	Initial	Oct 1998	Nov 2001	Nov 2004	Mar 2007	Jan 2012	Oct 2013	May 2015	Oct 2015
Blanco_R020F	2	2	1	2	2	-	2	2	2
Blanco_R020H	3	3	2	3	3	-	3	3	3
Blanco_R030J	1	1	1	1	1	-	1	1	1
Blanco_R030L	2	2	2	2	2	-	2	2	2
Blanco_R030M	1	1	1	1	1	-	1	1	1
Blanco_R040O	2	2	3	2	2	-	2	2	2
Blanco_R040P	3	3	4	3	3	-	3	3	3
Blanco_R040R	5	5	6	5	5	-	5	5	5
Blanco_R050S	3	3	4	3	3	-	3	3	3
Blanco_R050T	5	5	6	5	5	-	5	5	5
LittleBlanco_R020V	2	2	2	2	2	-	2	2	2
LittleBlanco_R030W	3	3	3	3	3	-	3	3	3
LittleBlanco_R030X	3	3	3	3	3	-	3	3	3
LittleBlanco_R040Y	5	5	4	5	5	-	5	5	5
Blanco_R060Z	1	1	1	1	1	-	1	1	1
Blanco_R070	5	4	8	5	4	-	7	5	7
Blanco_R080	4	3	6	4	3	-	6	4	6
Blanco_R090	4	3	7	4	4	-	7	4	7
Blanco_R100	2	2	3	2	2	-	3	2	3
Blanco_R110	1	1	1	1	1	-	1	1	1
CypressCr_R0204C	1	1	1	1	1	-	1	1	1
CypressCr_R0206C	1	1	1	1	1	-	1	1	1
CypressCr_R0206CL	1	1	1	1	1	-	1	1	1
CypressCr_R02010C	1	1	2	1	1	-	1	1	2
CypressCr_R03012C	1	1	2	1	1	-	1	1	2
CypressCr_R03014C	1	1	4	1	1	-	1	1	4
CypressCr_R03016C	1	1	4	1	1	-	1	1	4
Blanco_R120	2	2	1	1	3	-	2	3	2
Blanco_R130	5	5	1	1	6	-	5	8	5
Blanco_R140	5	5	1	1	6	-	6	8	5
Blanco_R150	4	4	1	1	5	-	4	6	4
Blanco_R160a	2	2	2	2	2	-	2	2	2
Blanco_R160b	3	3	3	3	3	-	3	3	3
Blanco_R170	6	6	4	4	6	-	6	6	6
SinkCk_R010	1	1	-	1	1	1	-	1	1
SinkCk_R020	1	1	-	1	1	1	-	1	1
SinkCk_R030	1	1	-	1	1	1	-	1	1
SinkCk_R040	1	1	-	1	1	1	-	1	1
SinkCk_R050	1	1	-	1	1	1	-	1	1
SanMarcos_R003	1	1	-	1	1	1	-	1	1
SanMarcos_R005	1	1	-	1	1	1	-	1	1
SanMarcos_R007	1	1	-	1	1	1	-	1	1
SanMarcos_R020	8	8	-	8	8	8	-	8	8
SanMarcos_R030	5	5	-	5	5	5	-	5	5
SanMarcos_R040	2	1	-	1	1	1	-	1	1
PlumCr_R010	8	6	-	6	6	6	-	6	6
PlumCr_R020	6	3	-	3	3	3	-	3	3
SanMarcos_R050	7	3	-	3	3	3	-	3	3

6.4.3 Calibration Results

The final calibration results showed that the HEC-HMS model was able to accurately simulate the response of the watershed, as it reproduced the volume, timing, shape, and peak magnitudes of most observed floods very well. The resulting hydrograph comparisons can be seen in the following figures of this section. The figures show the HEC-HMS computed versus the USGS observed flow hydrographs at each gage location. Figures are only shown for the locations where the USGS stream gages were recording for that event and where the magnitude of the flow was significant enough to warrant calibration. In some cases, only a single black dot appears for the observed flow. These are cases where the gage was not recording, but the USGS did estimate the peak flow of that flood event.

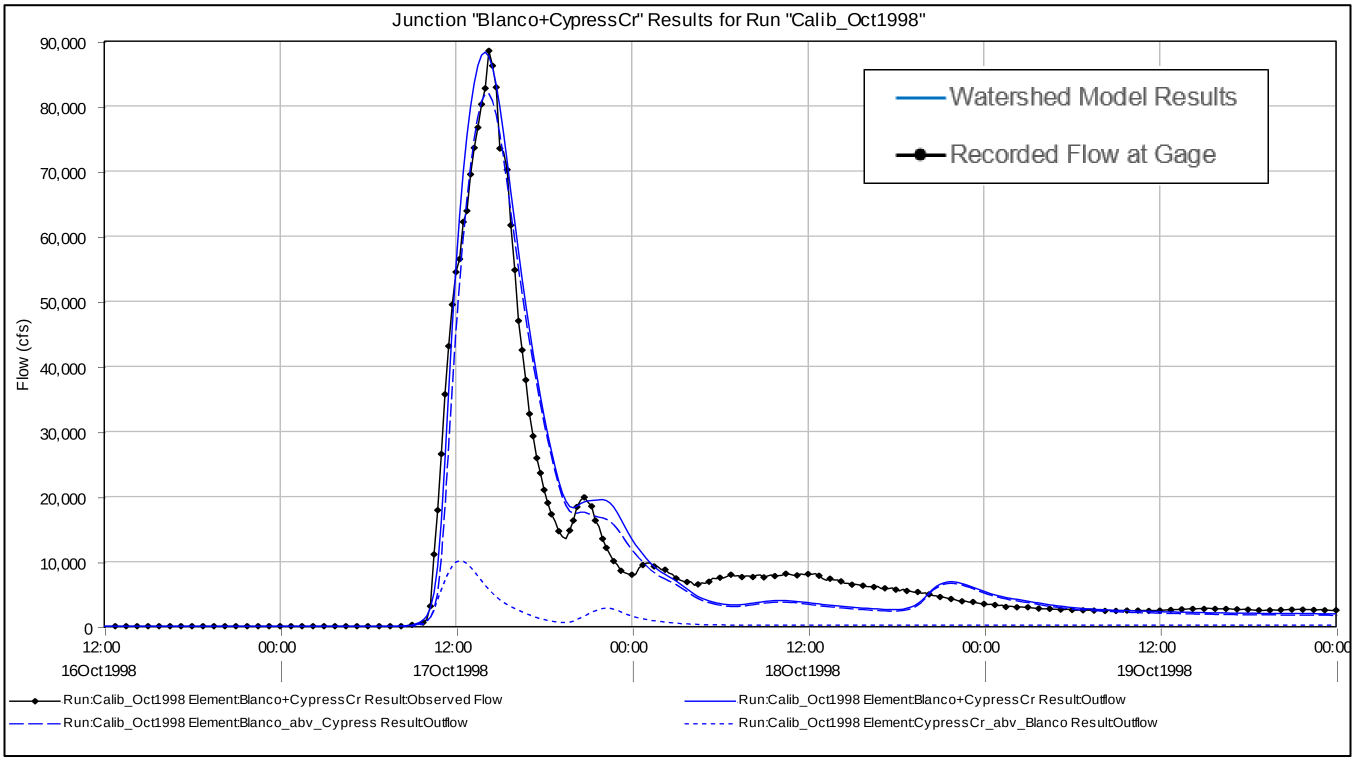

Figure 6.11: Oct 1998 Calibration Results for the Blanco River at Wimberley, TX

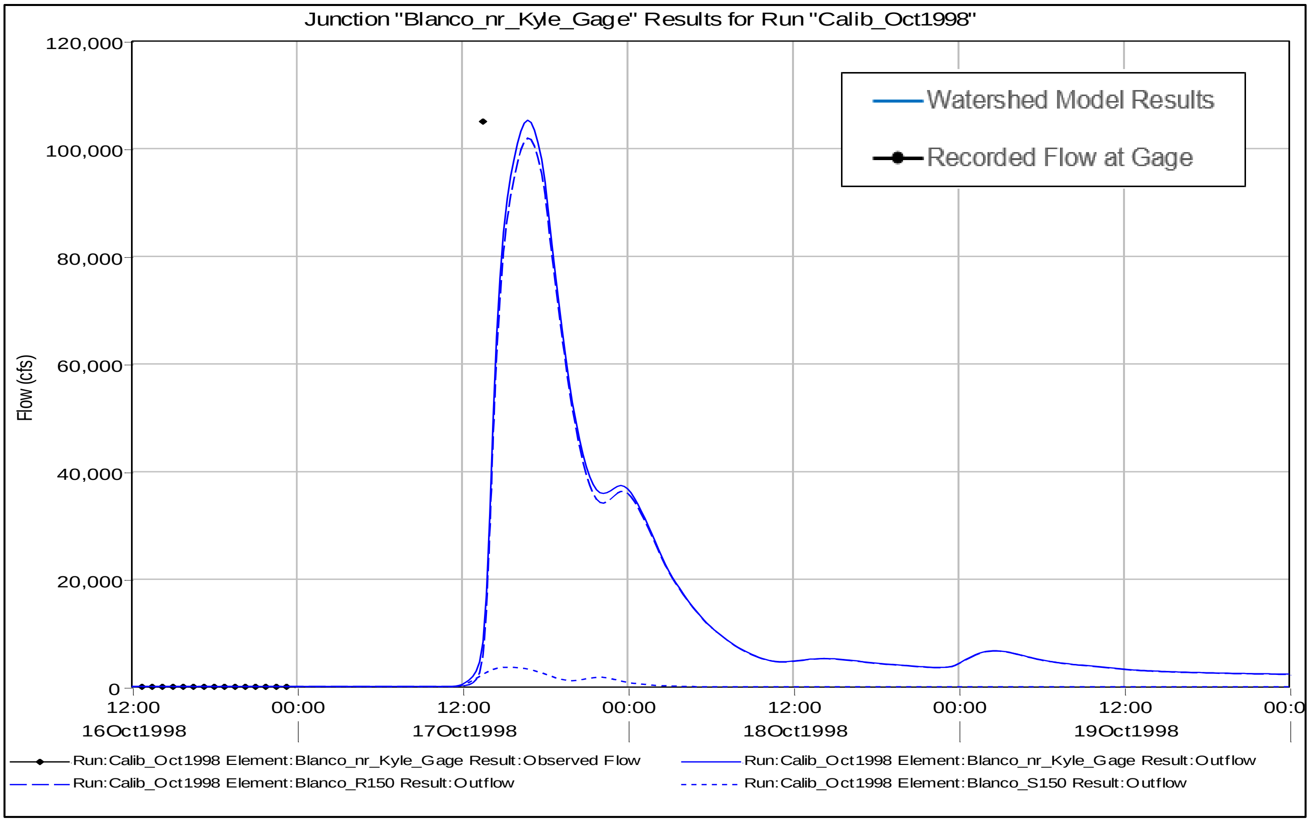

Figure 6.12: Oct 1998 Calibration Results for the Blanco River near Kyle, TX

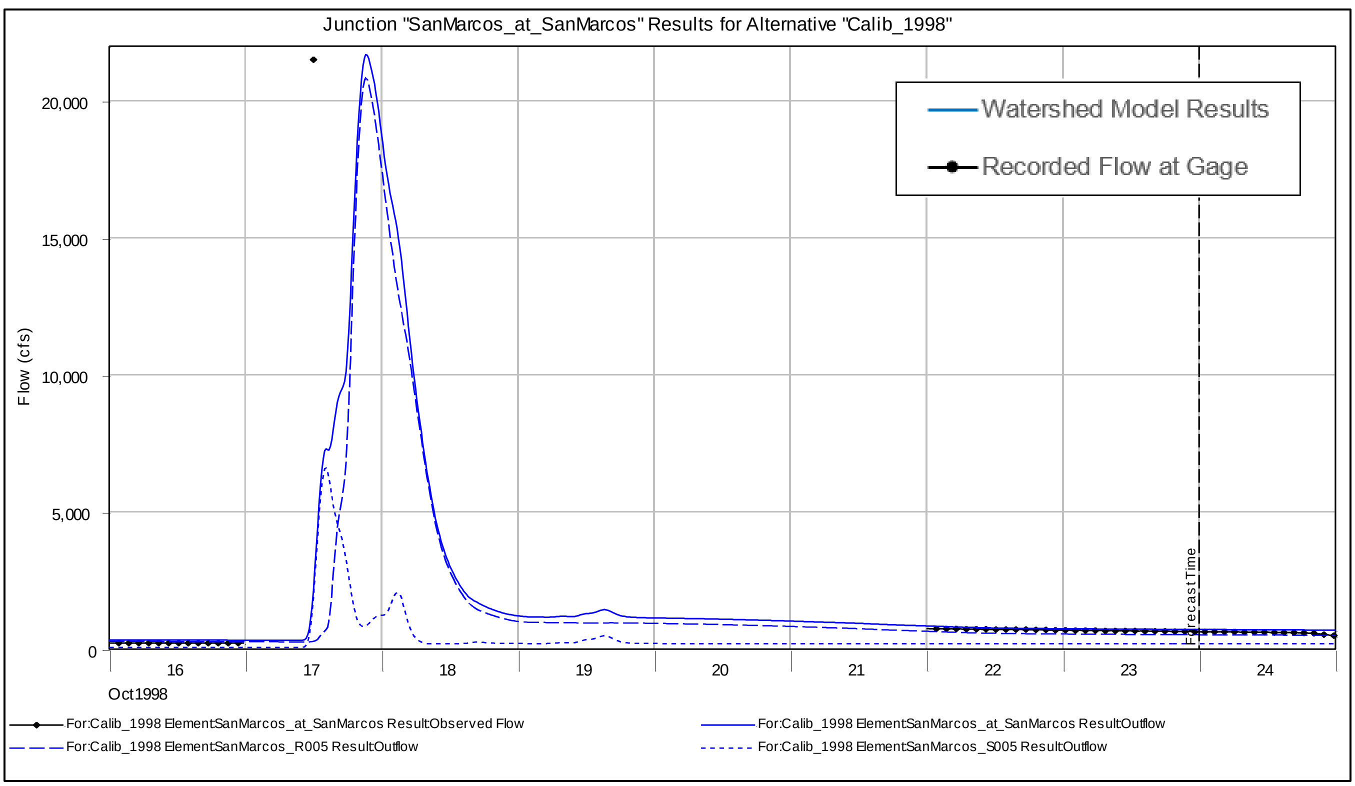

Figure 6.13: Oct 1998 Calibration Results for the San Marcos River at San Marcos, TX

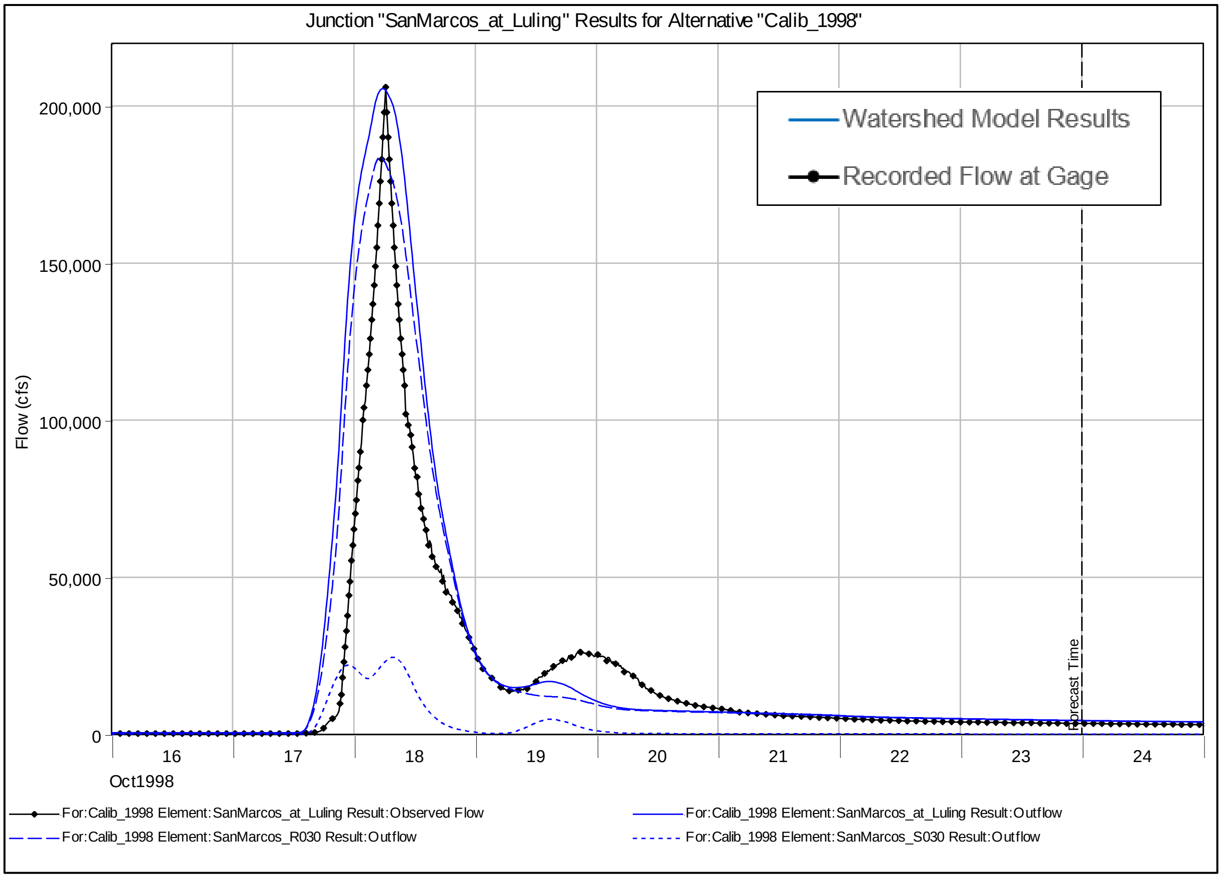

Figure 6.14: Oct 1998 Calibration Results for the San Marcos River at Luling, TX

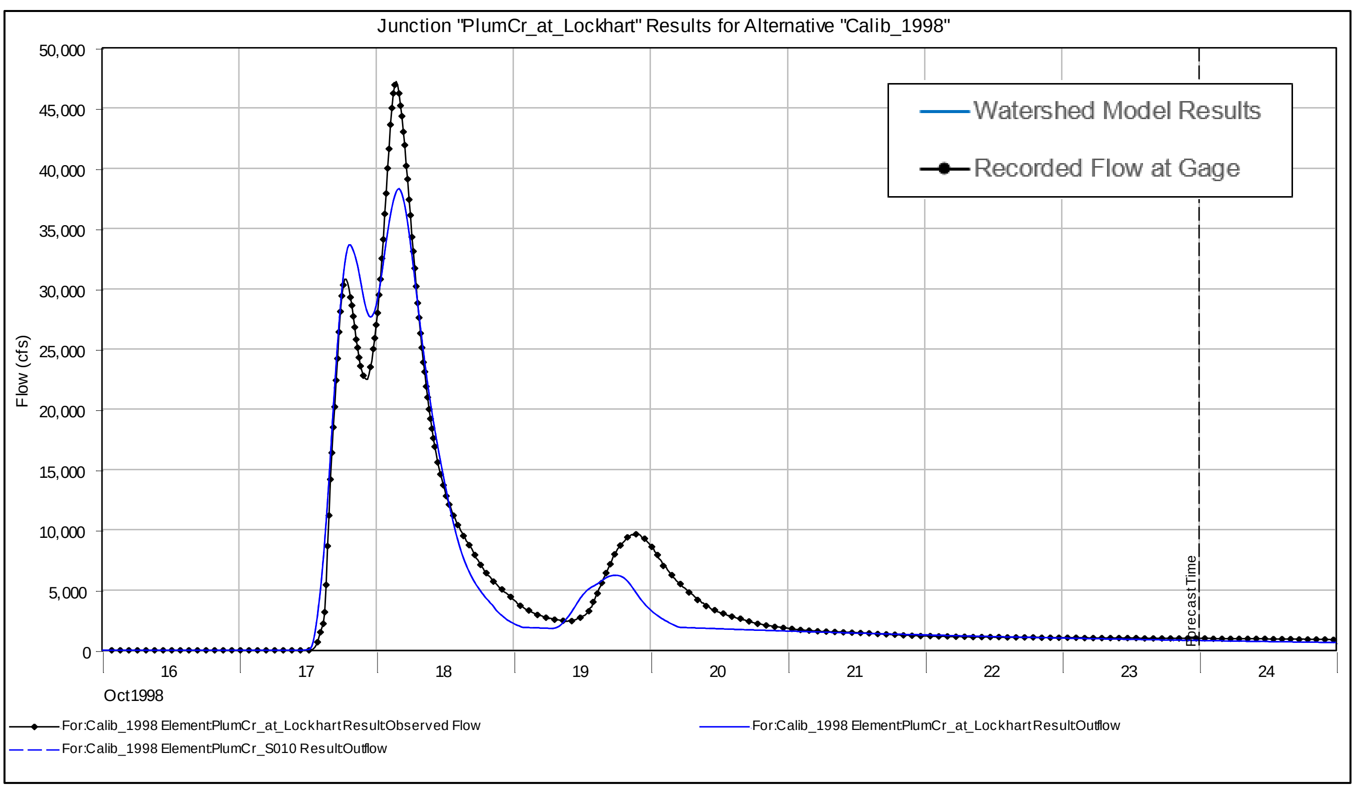

Figure 6.15: Oct 1998 Calibration Results for Plum Creek at Lockhart, TX

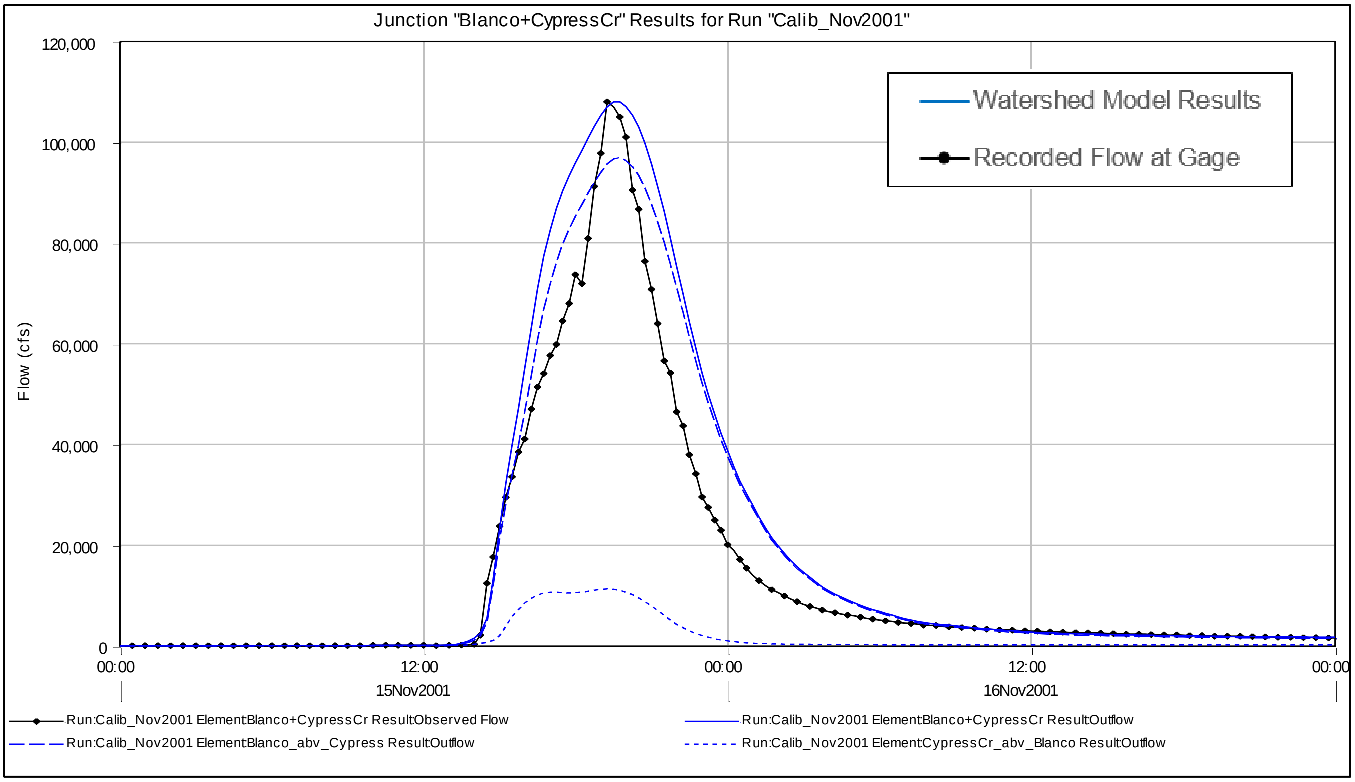

Figure 6.16: Nov 2001 Calibration Results for the Blanco River at Wimberley, TX

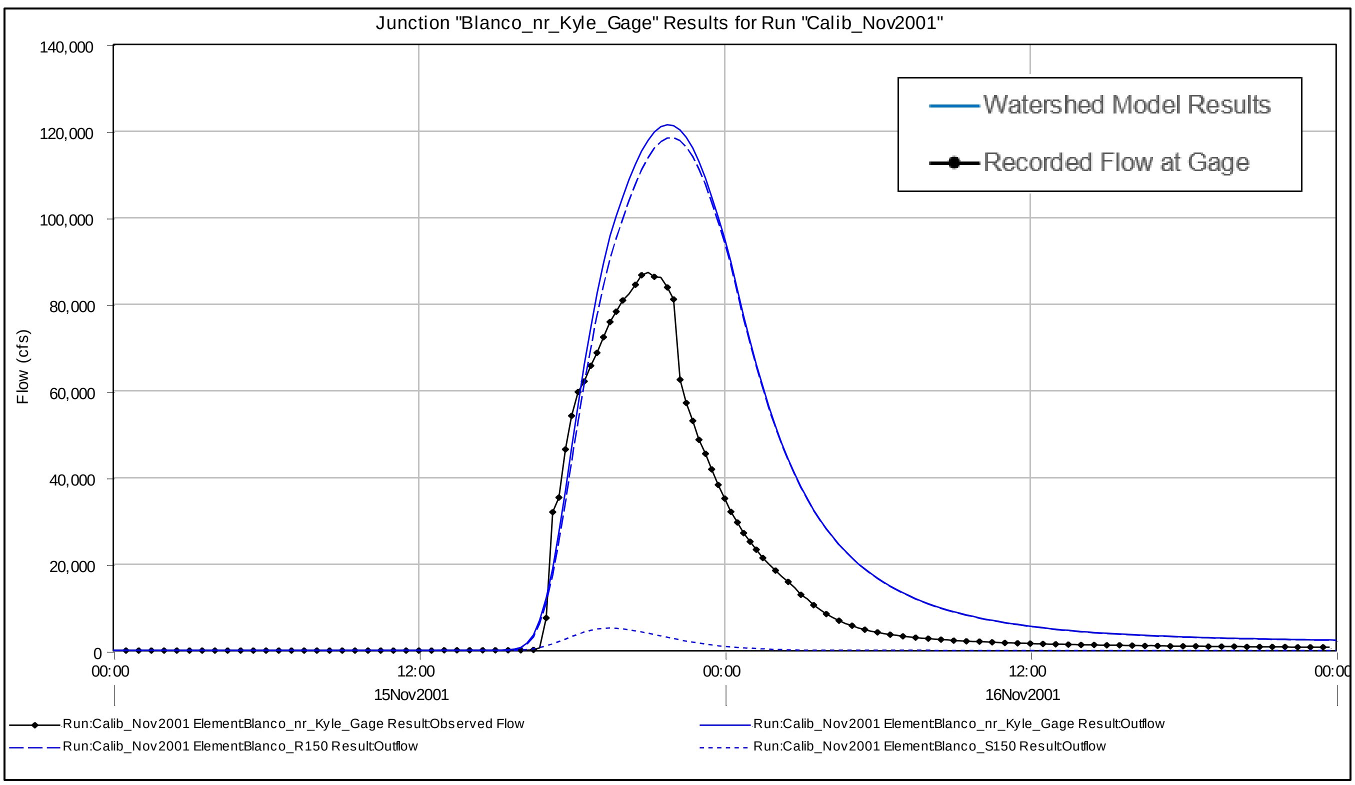

Figure 6.17: Nov 2001 Calibration Results for the Blanco River near Kyle, TX

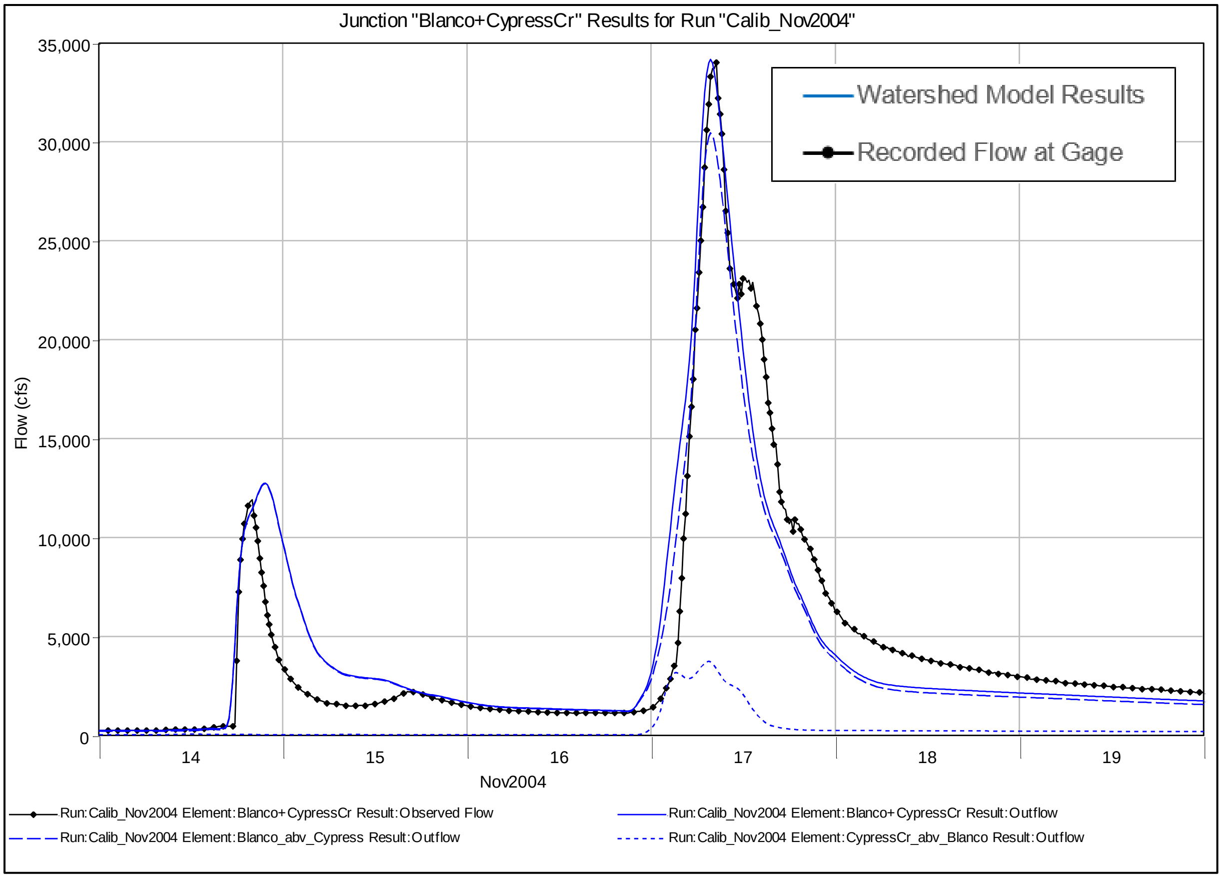

Figure 6.18: Nov 2004 Calibration Results for the Blanco River at Wimberley, TX

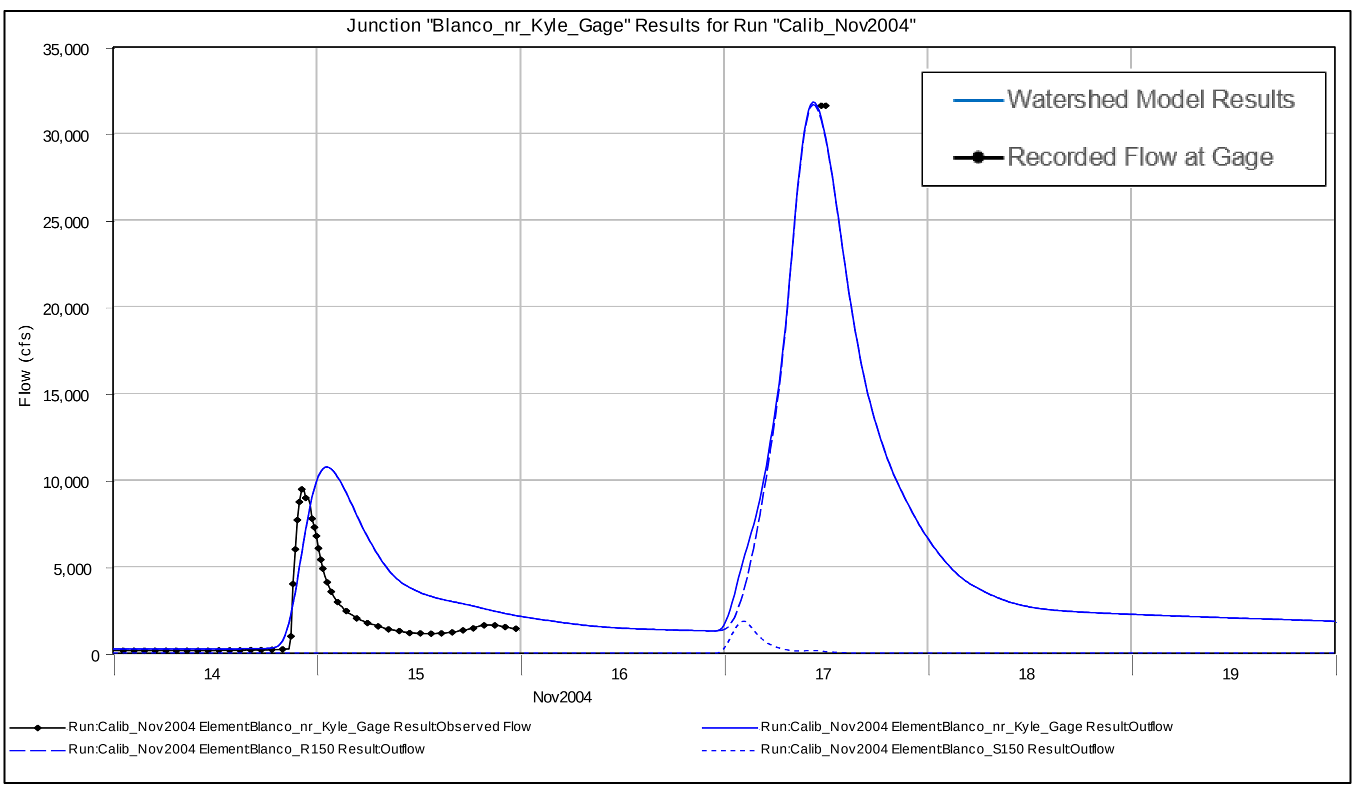

Figure 6.19: Nov 2004 Calibration Results for the Blanco River near Kyle, TX

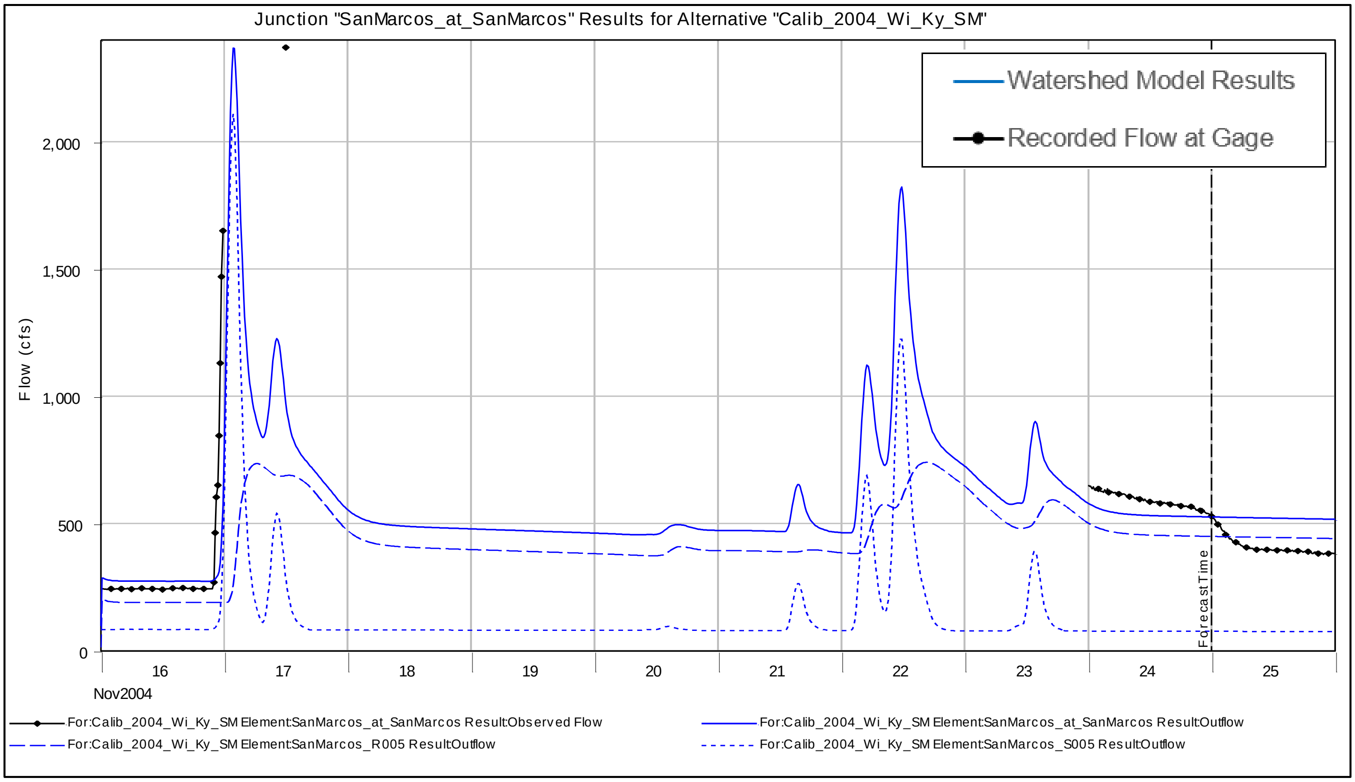

Figure 6.20: Nov 2004 Calibration Results for the San Marcos River at San Marcos, TX

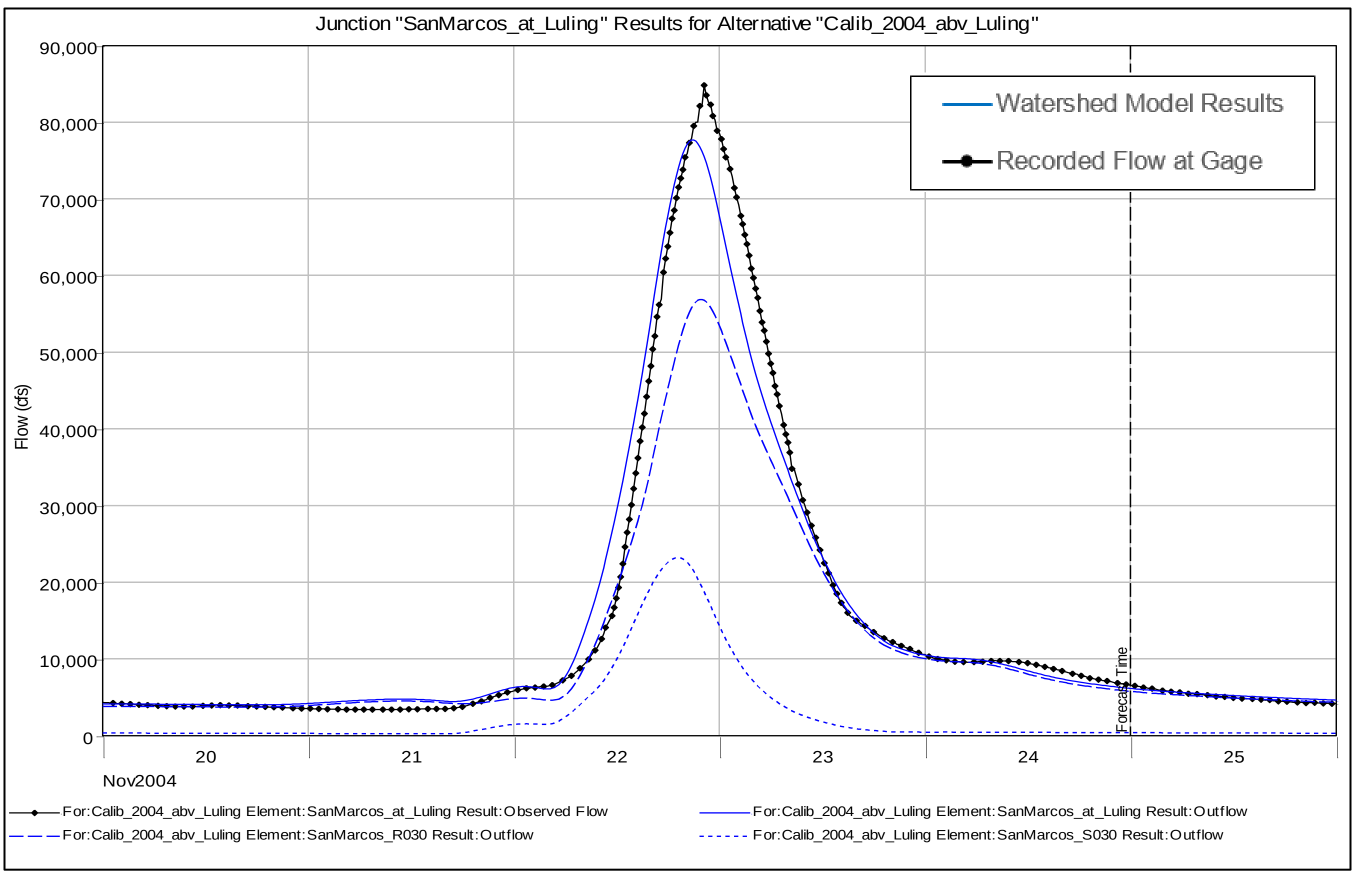

Figure 6.21: Nov 2004 Calibration Results for the San Marcos River at Luling, TX

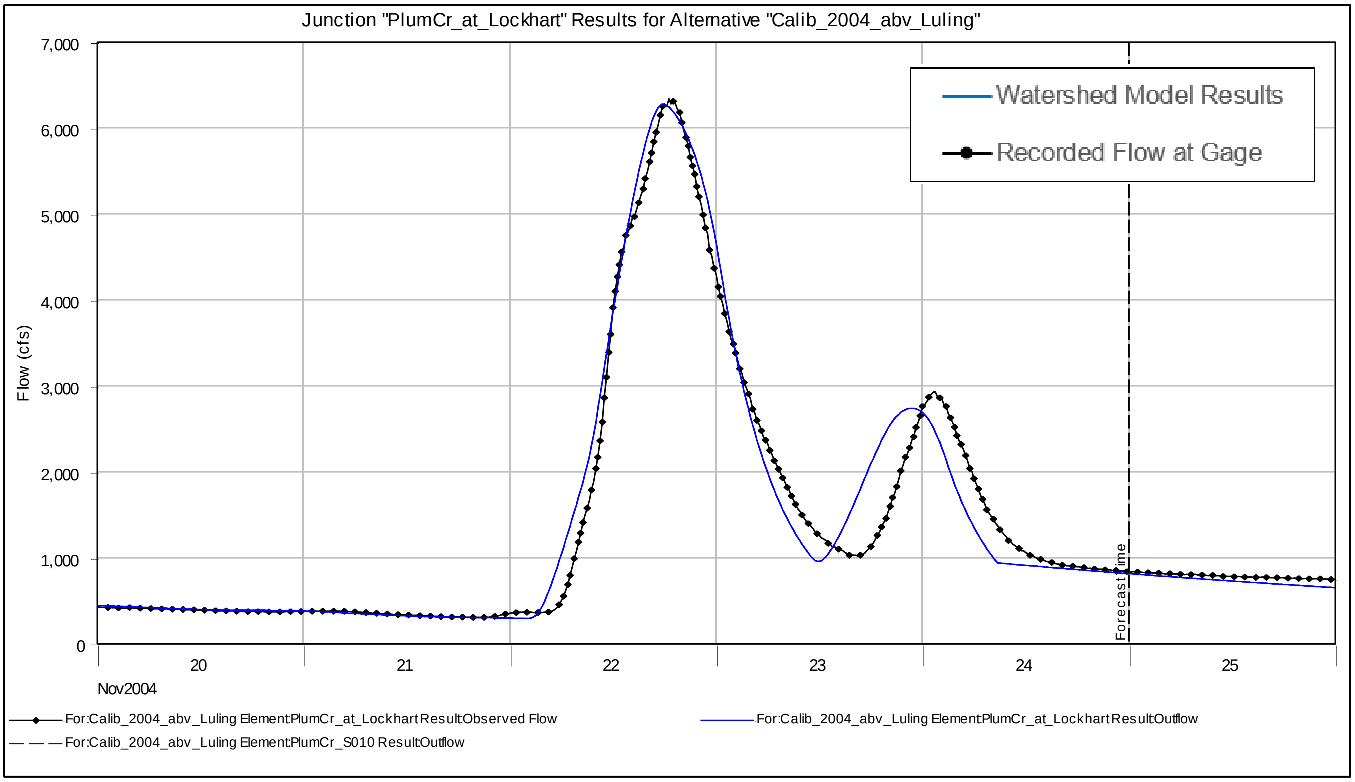

Figure 6.22: Nov 2004 Calibration Results for Plum Creek at Lockhart, TX

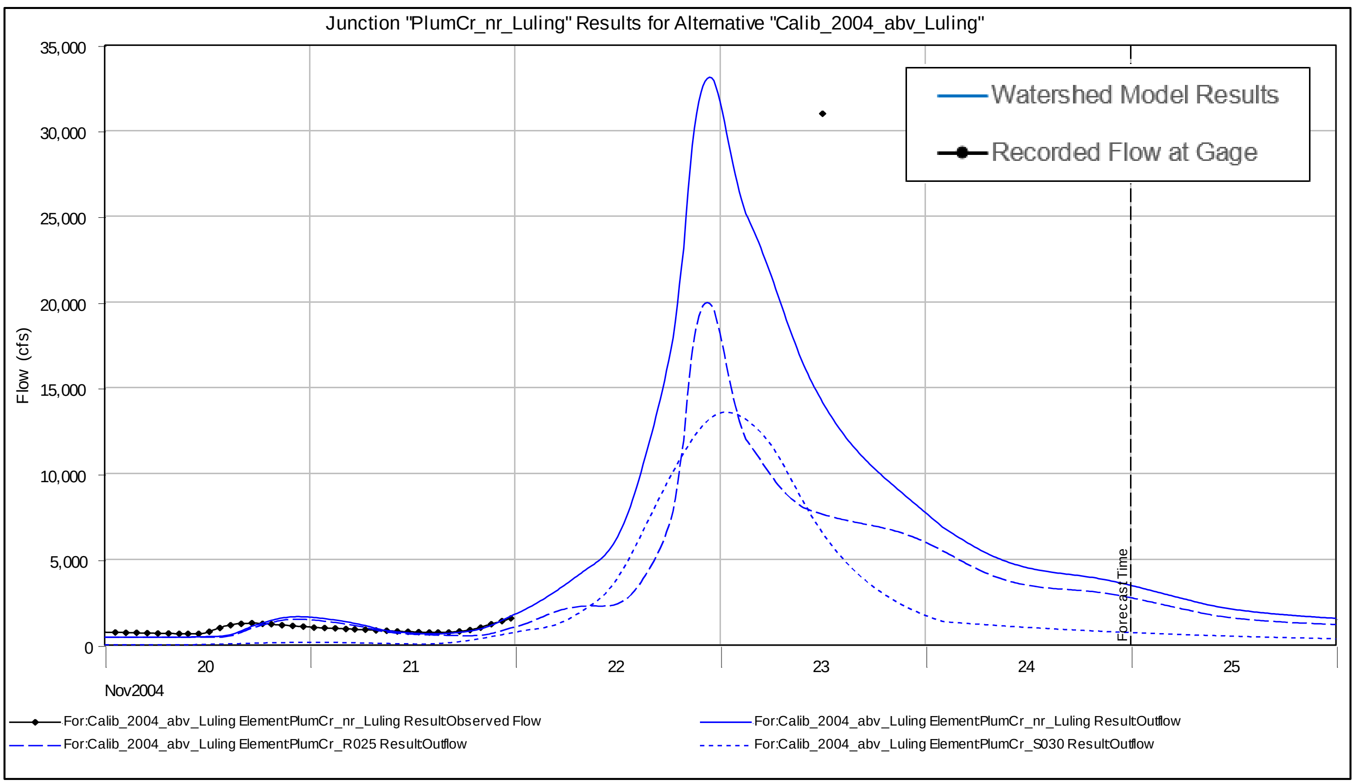

Figure 6.23: Nov 2004 Calibration Results for Plum Creek near Luling, TX

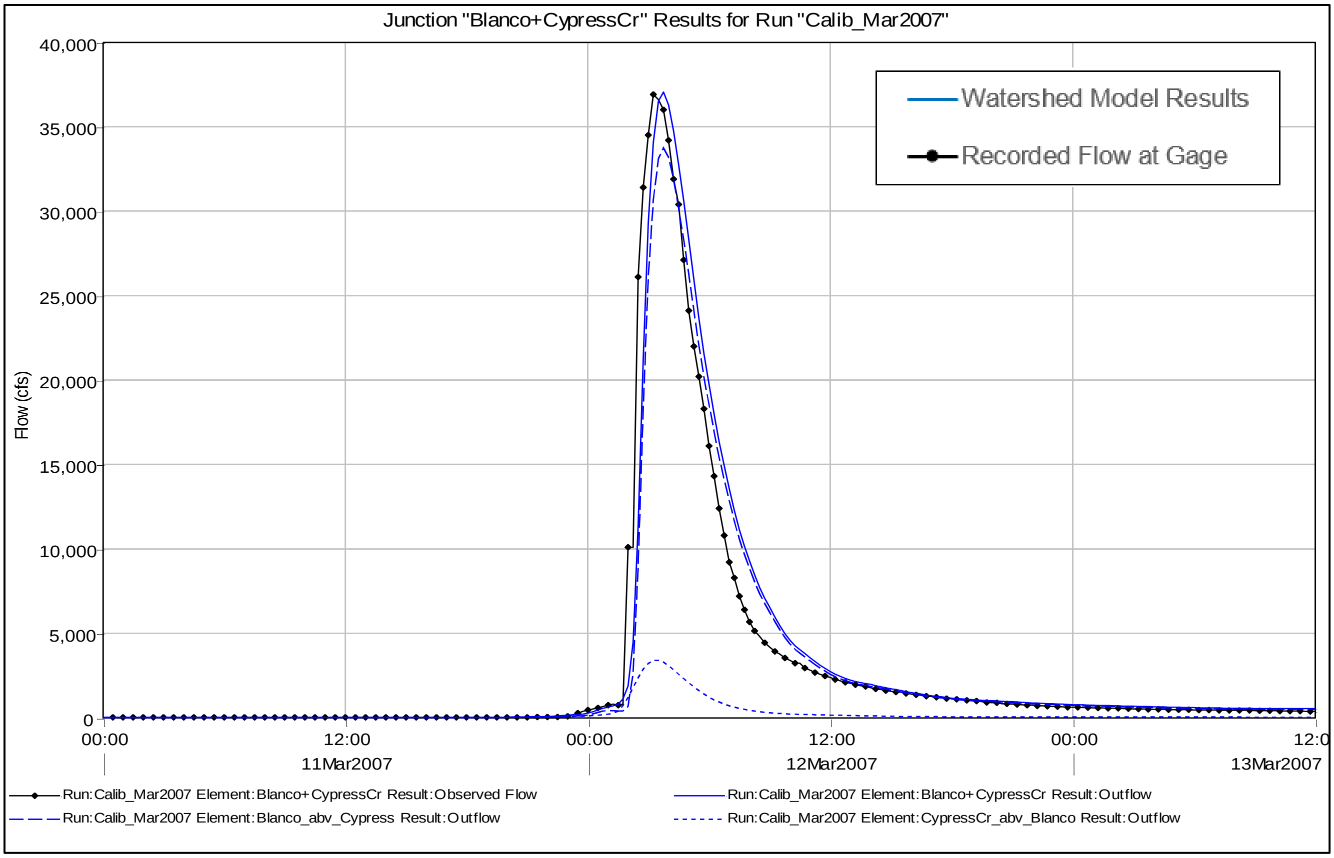

Figure 6.24: Mar 2007 Calibration Results for the Blanco River at Wimberley, TX

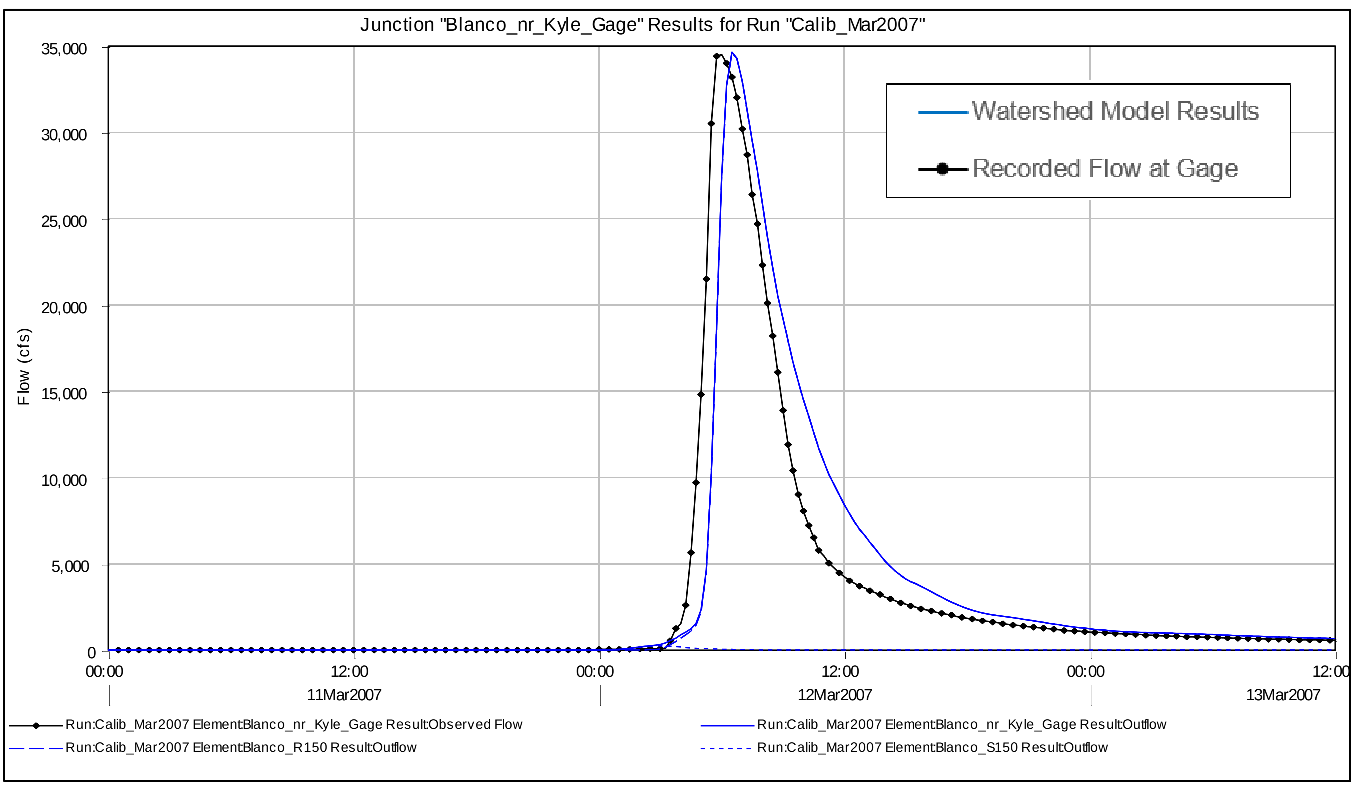

Figure 6.25: Mar 2007 Calibration Results for the Blanco River near Kyle, TX

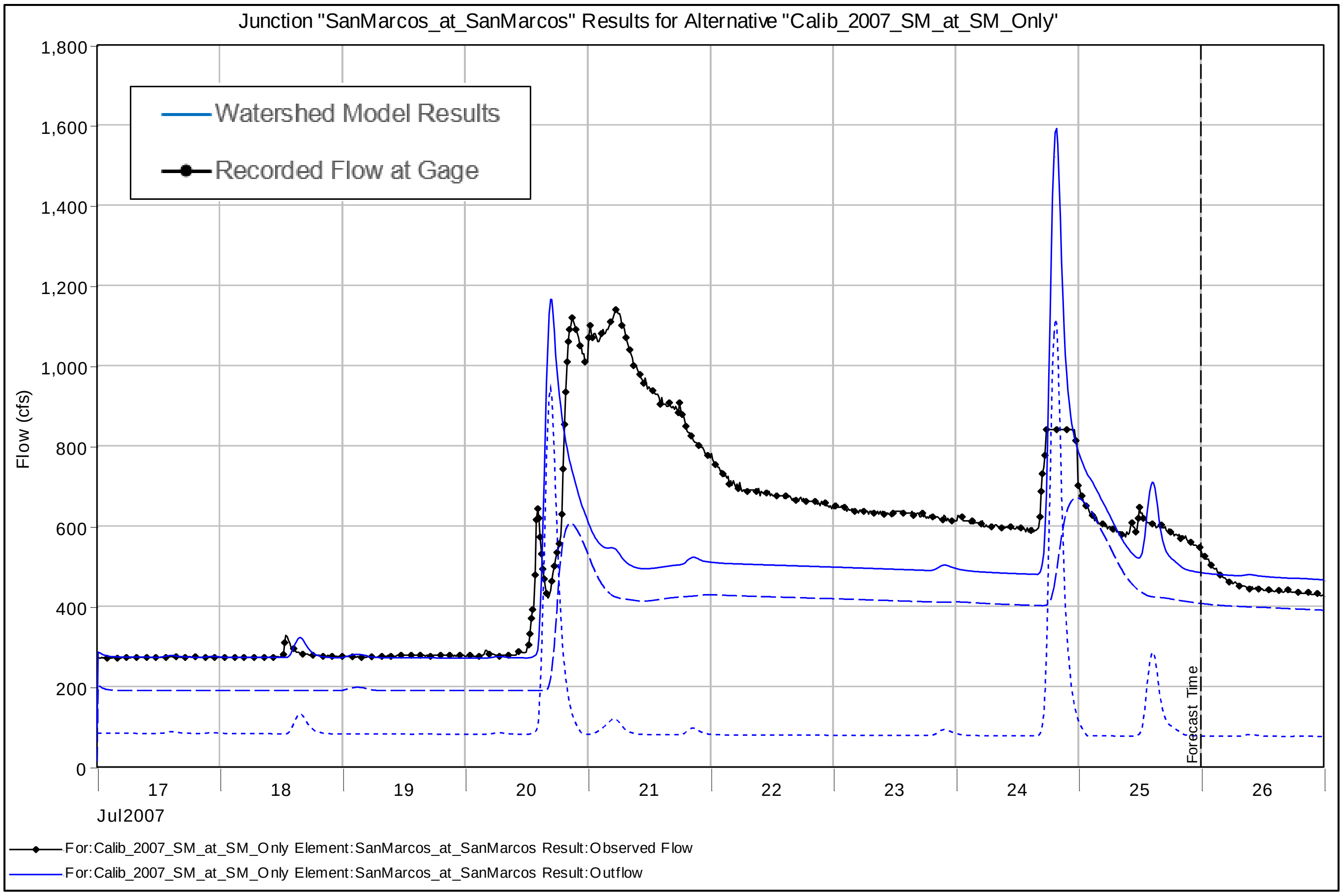

Figure 6.26: Mar 2007 Calibration Results for the San Marcos River at San Marcos, TX

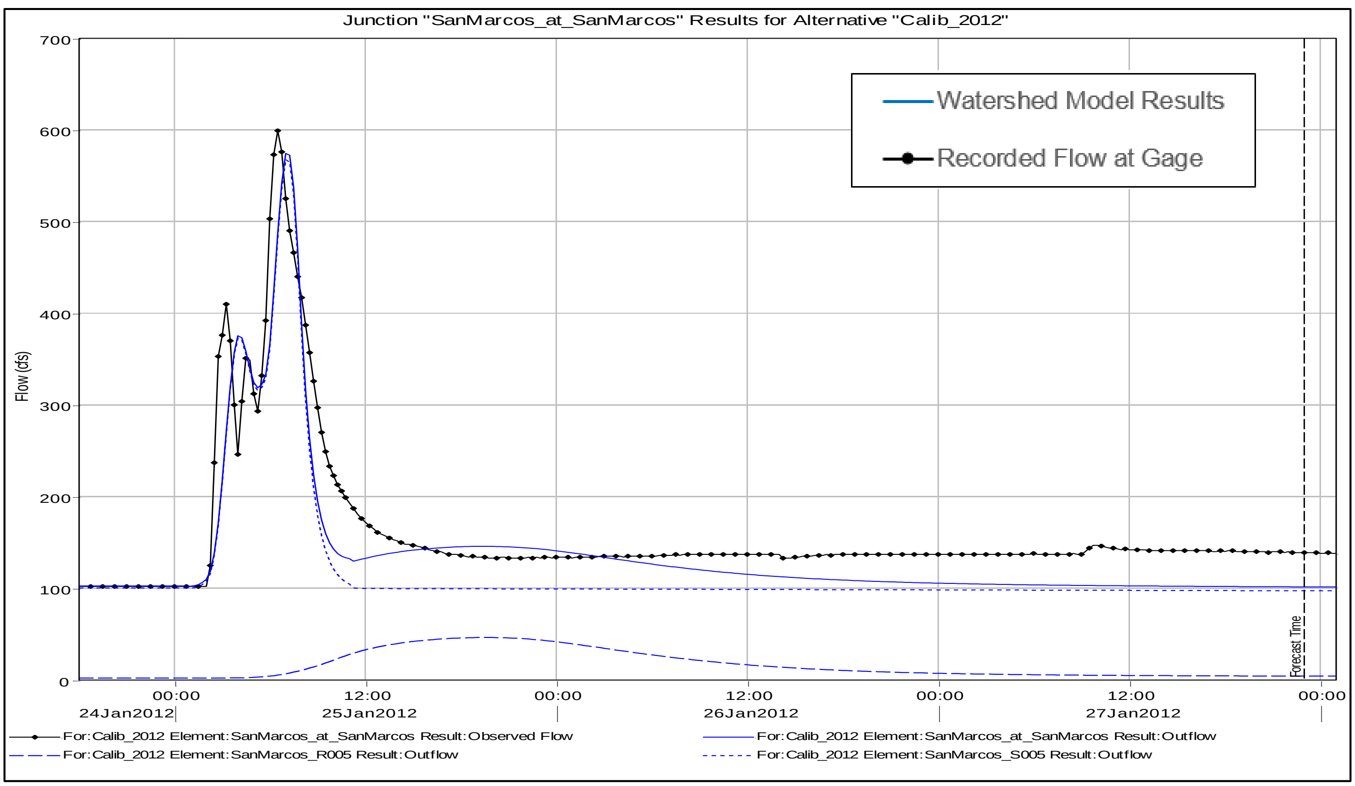

Figure 6.27: Jan 2012 Calibration Results for the San Marcos River at San Marcos, TX

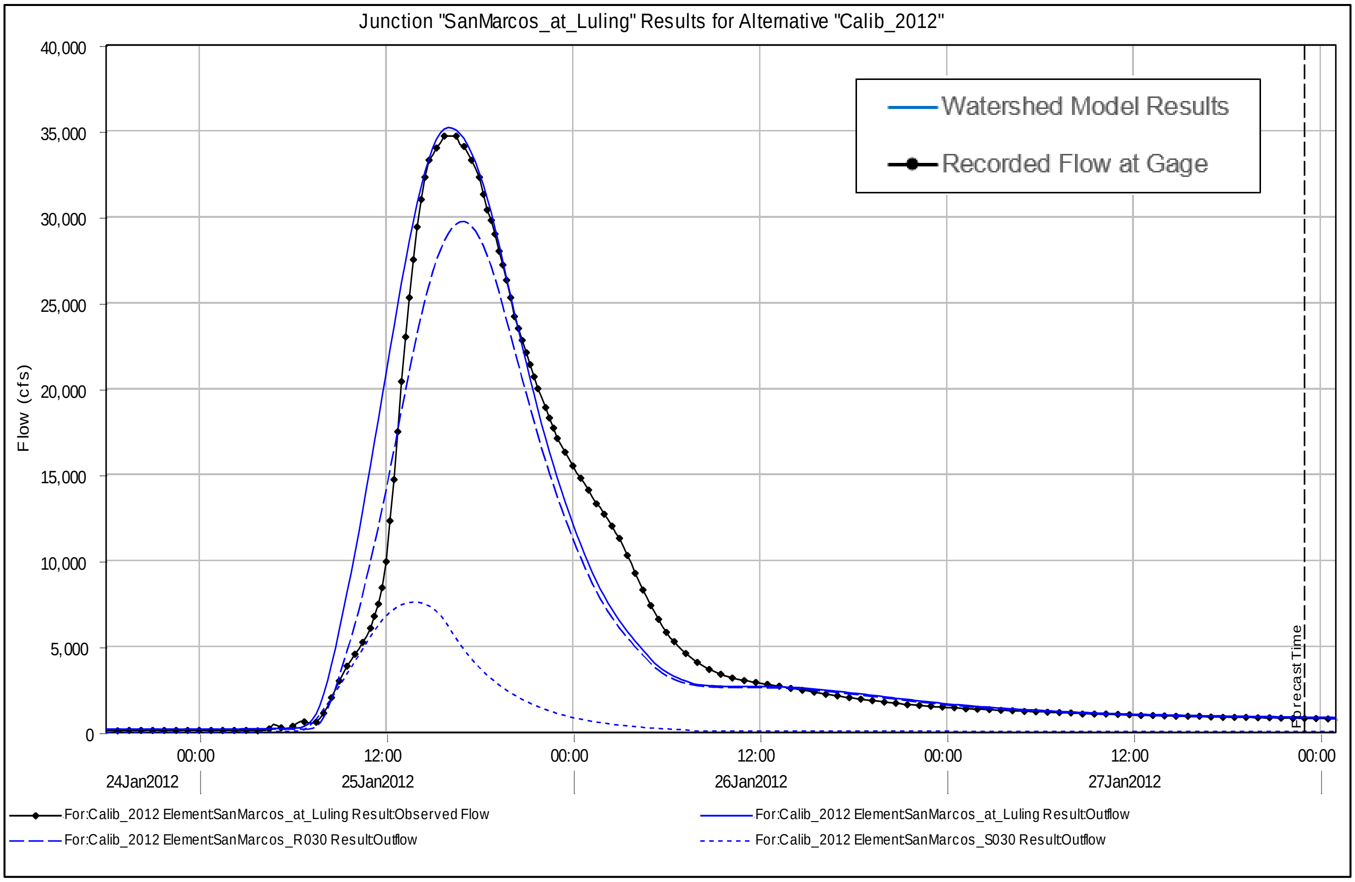

Figure 6.28: Jan 2012 Calibration Results for the San Marcos River at Luling, TX

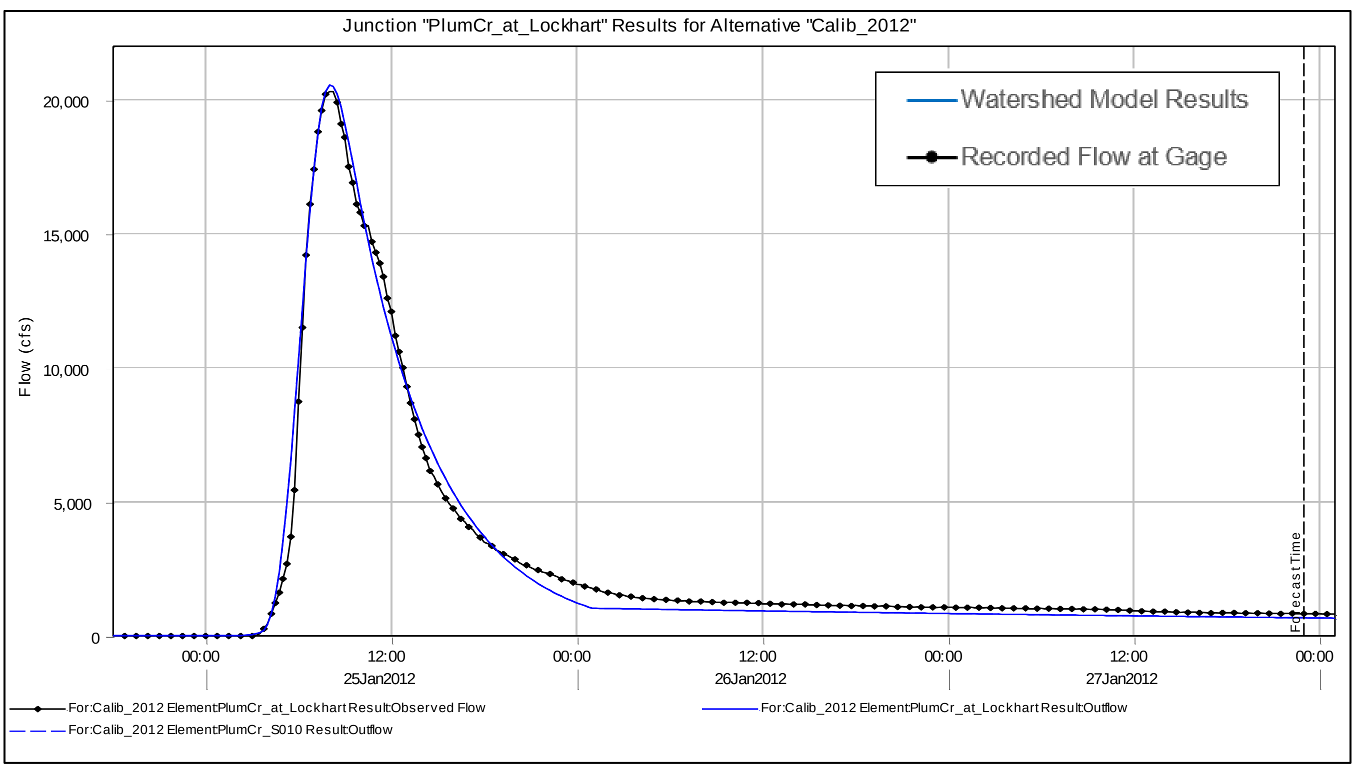

Figure 6.29: Jan 2012 Calibration Results for Plum Creek at Lockhart, TX

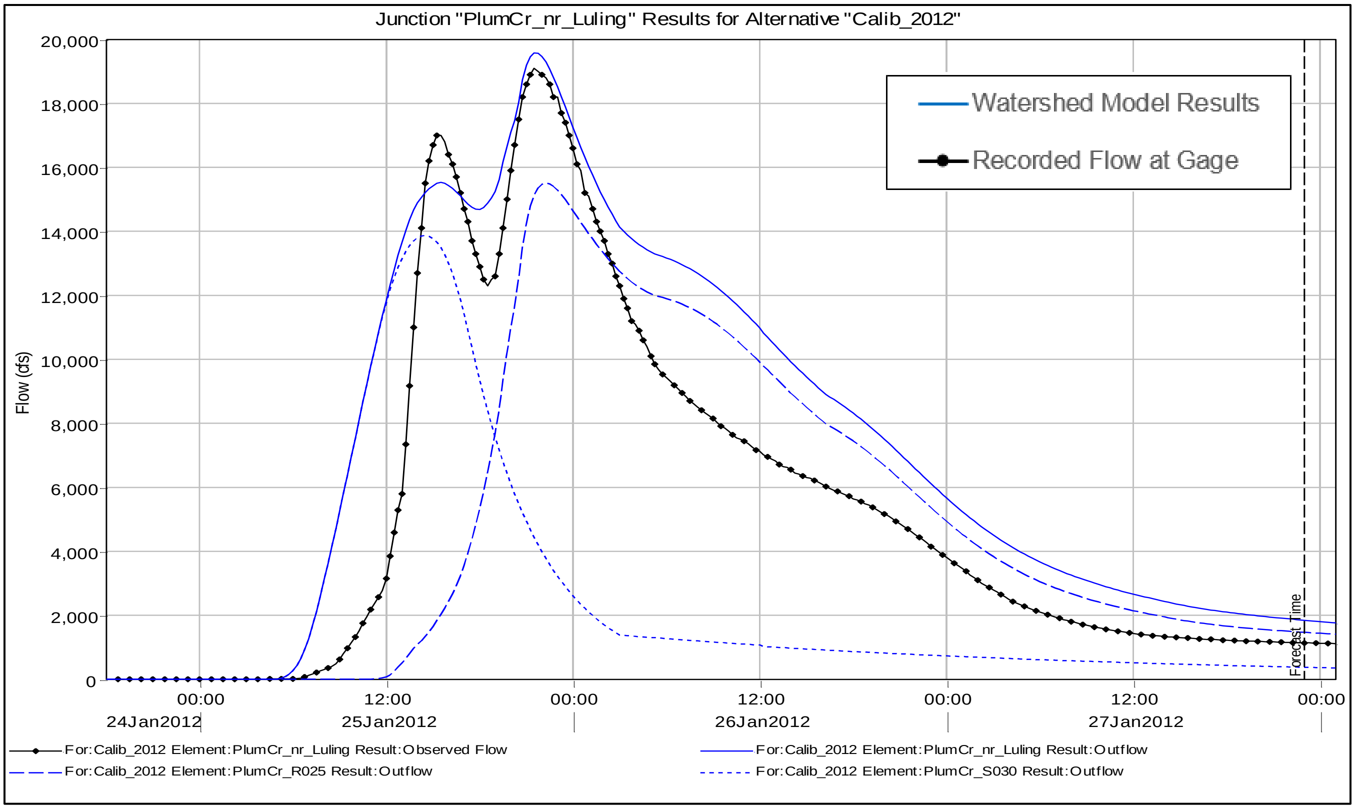

Figure 6.30: Jan 2012 Calibration Results for Plum Creek near Luling, TX

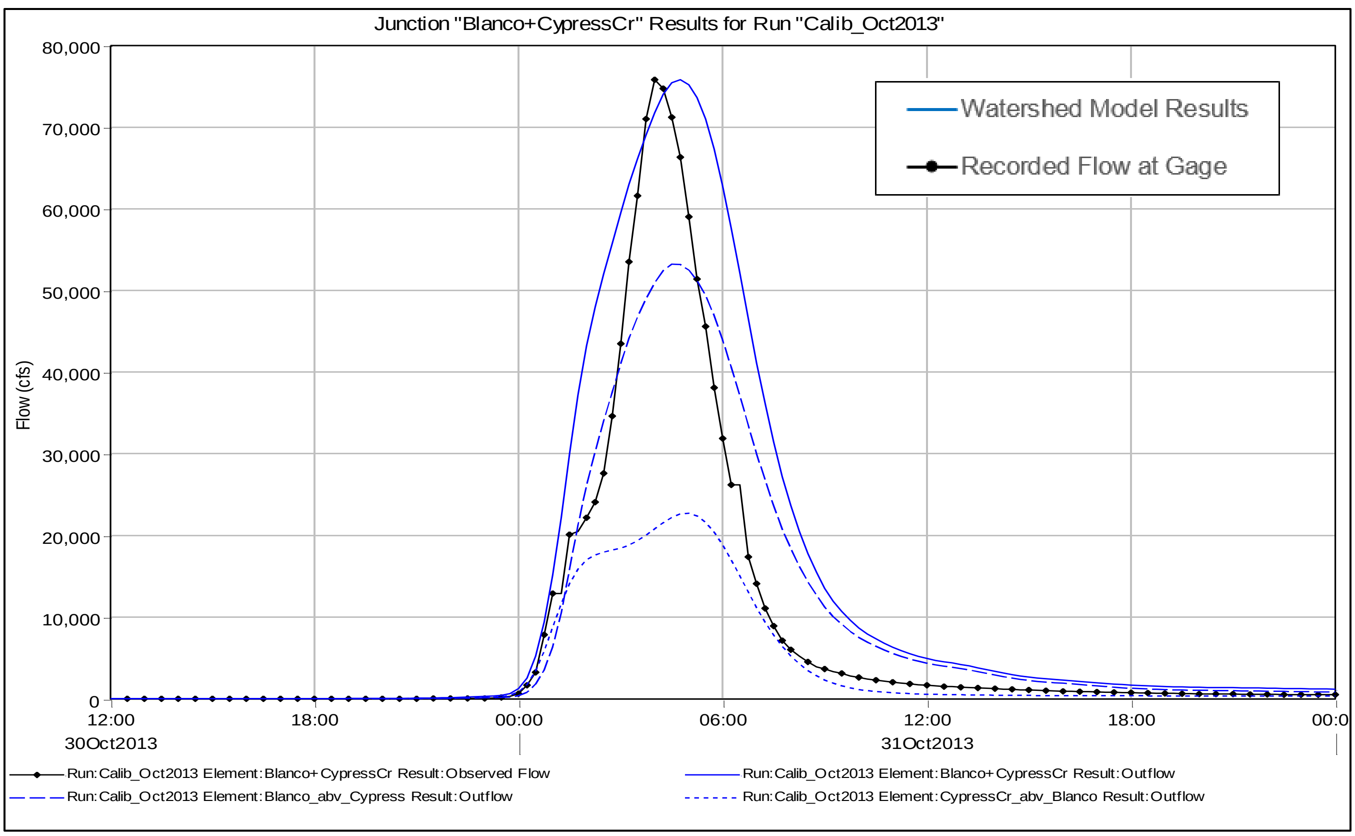

Figure 6.31: Oct 2013 Calibration Results for the Blanco River at Wimberley, TX

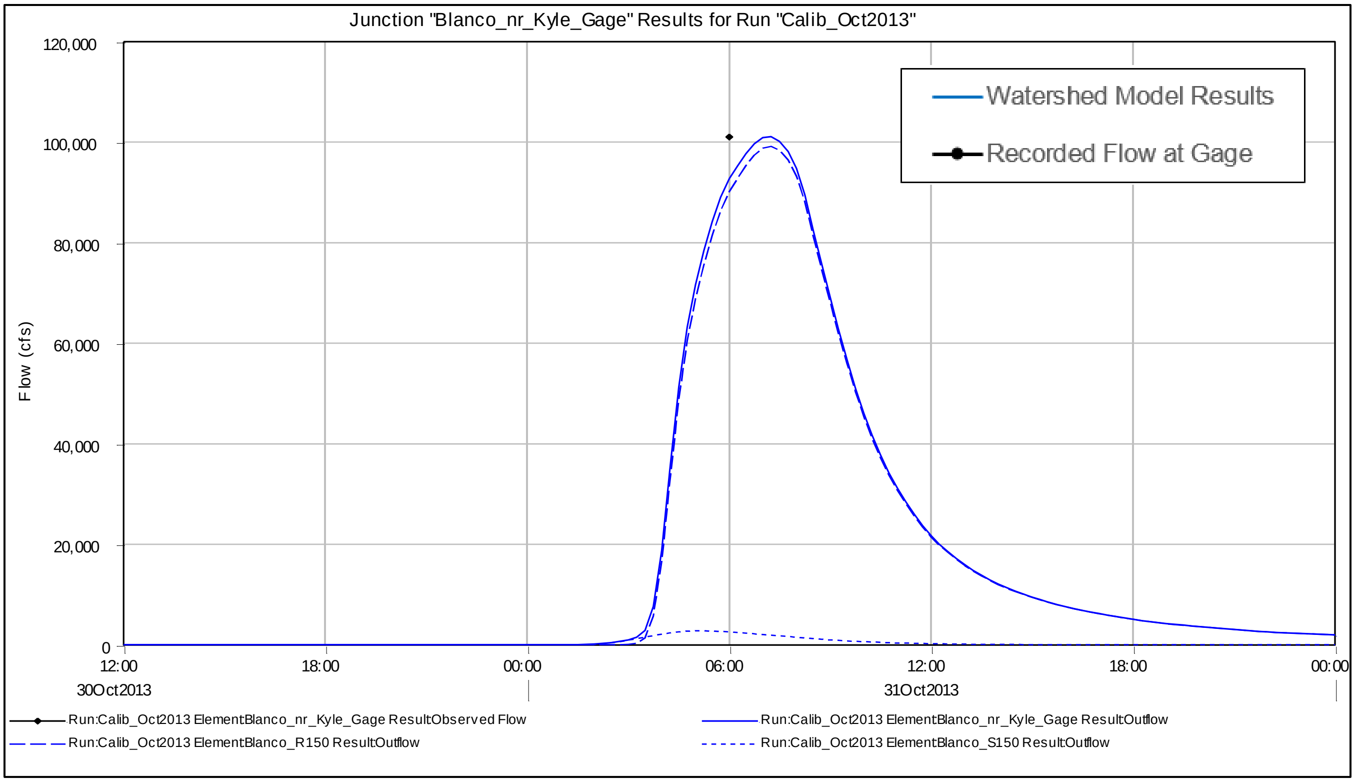

Figure 6.32: Oct 2013 Calibration Results for the Blanco River near Kyle, TX

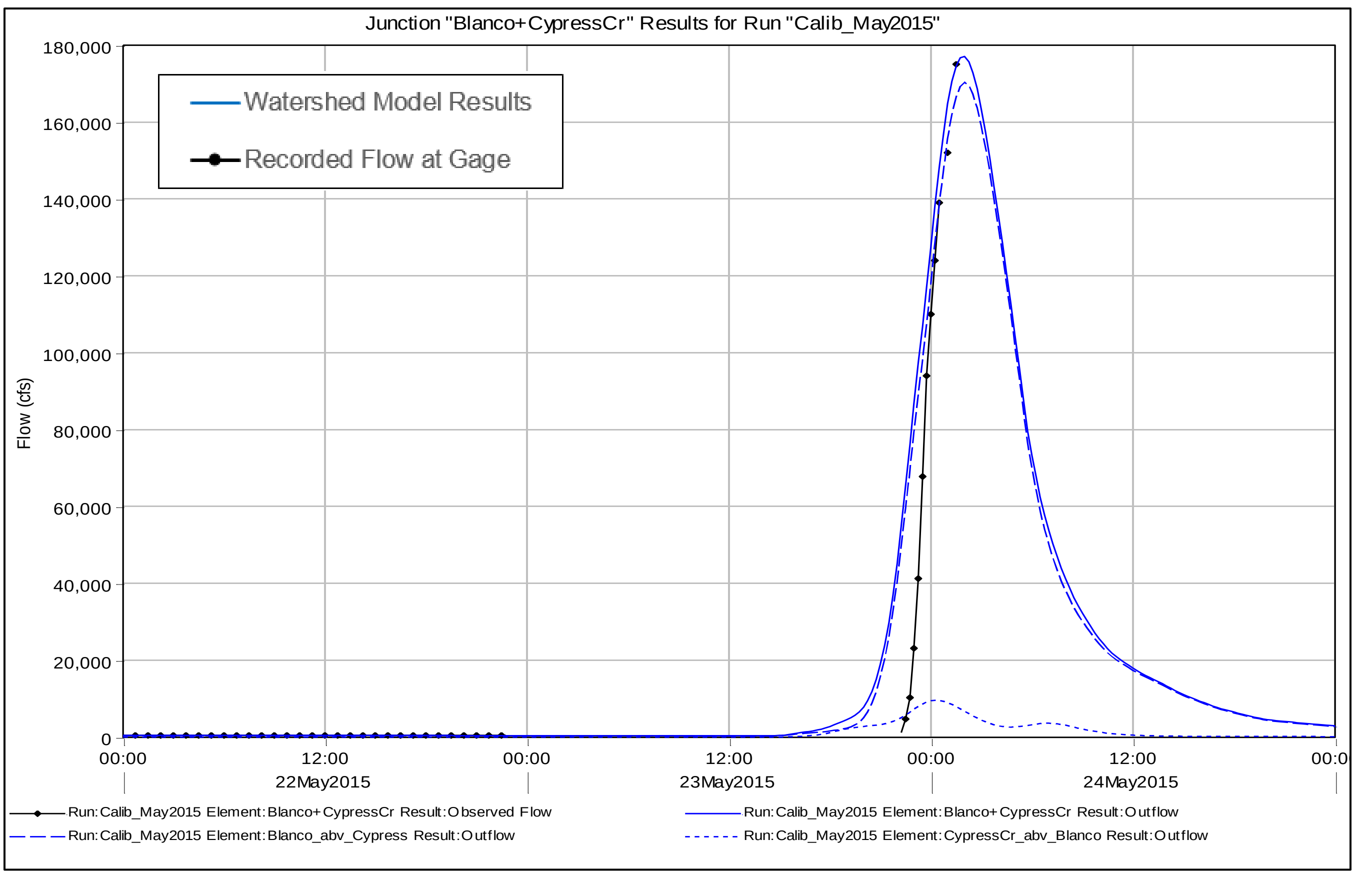

Figure 6.33: May 2015 Calibration Results for the Blanco River at Wimberley, TX

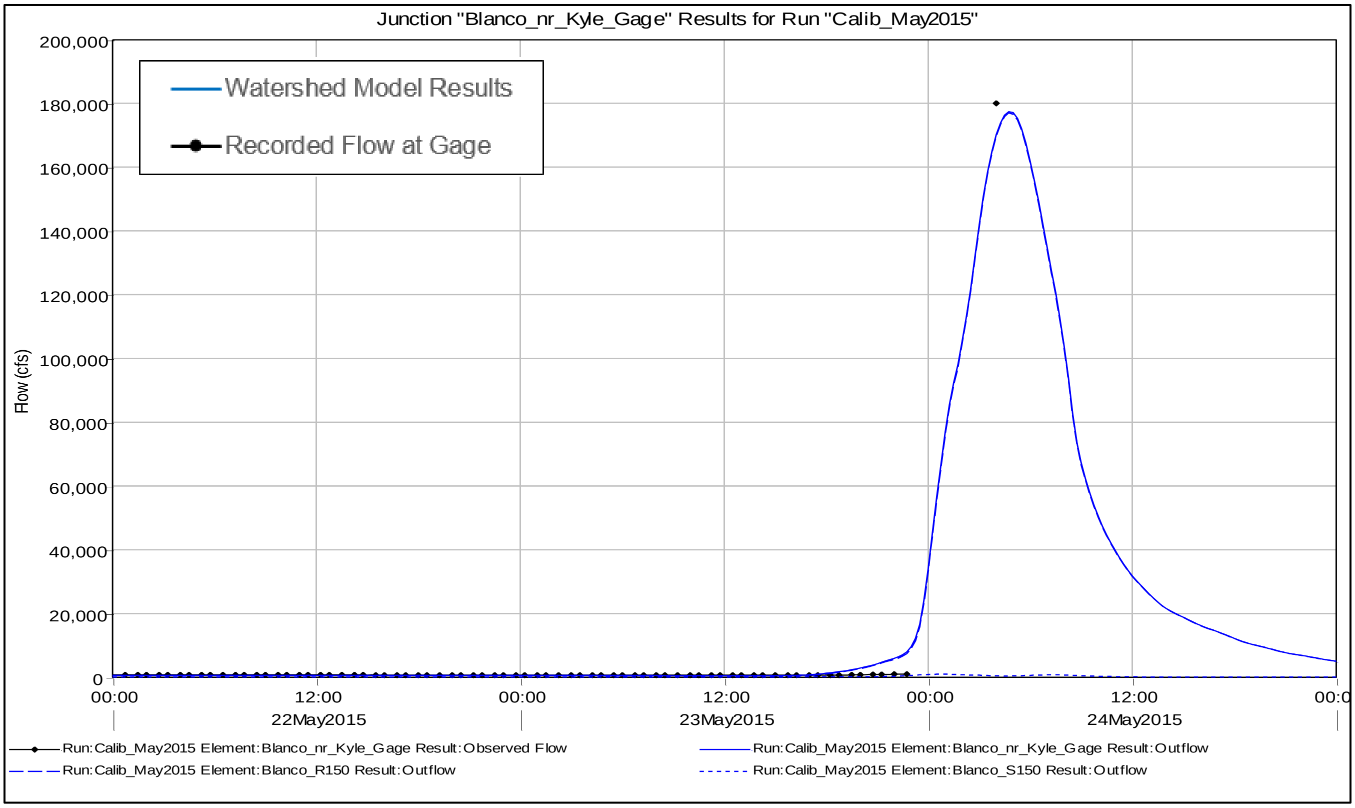

Figure 6.34: May 2015 Calibration Results for the Blanco River near Kyle, TX

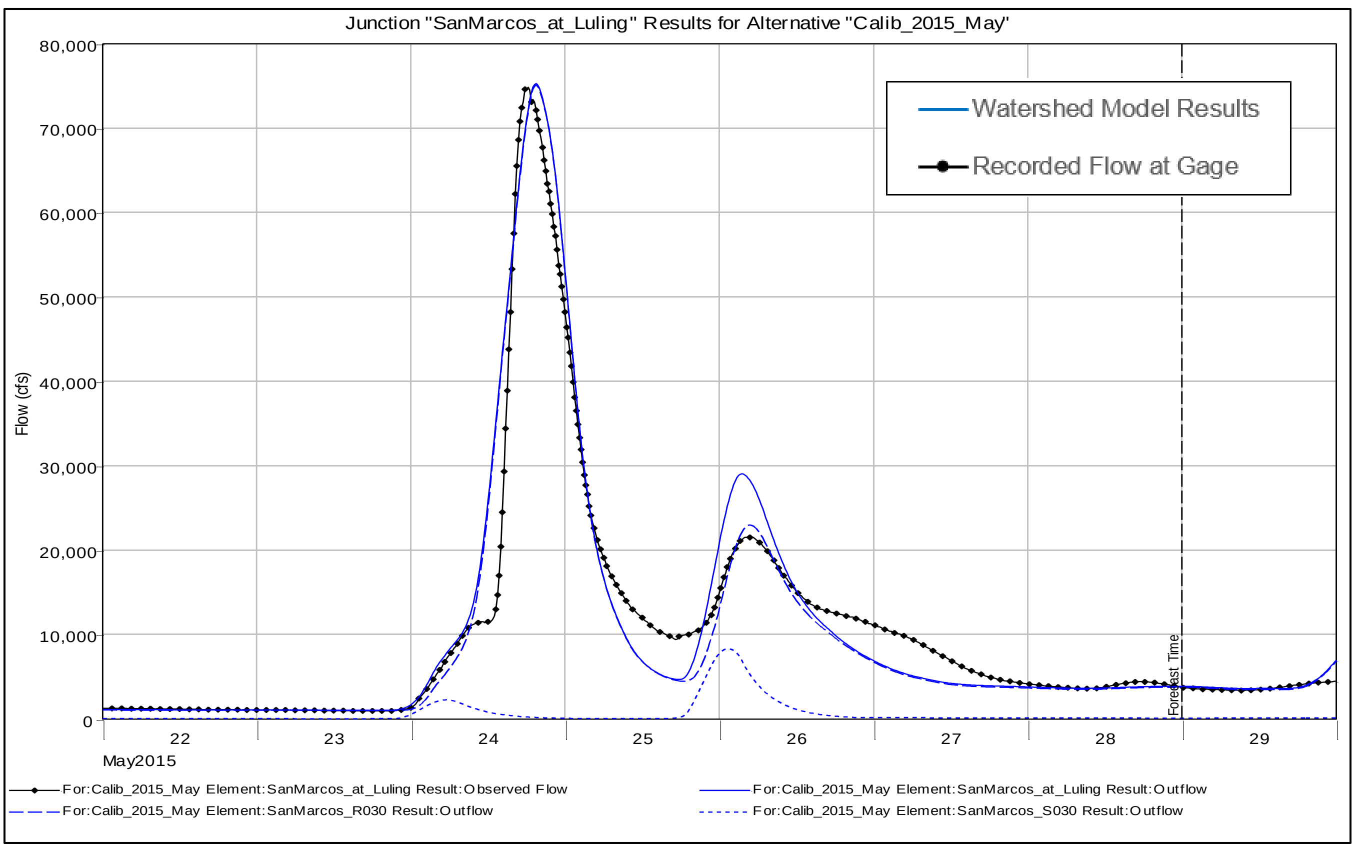

Figure 6.35: May 2015 Calibration Results for the San Marcos River at Luling, TX

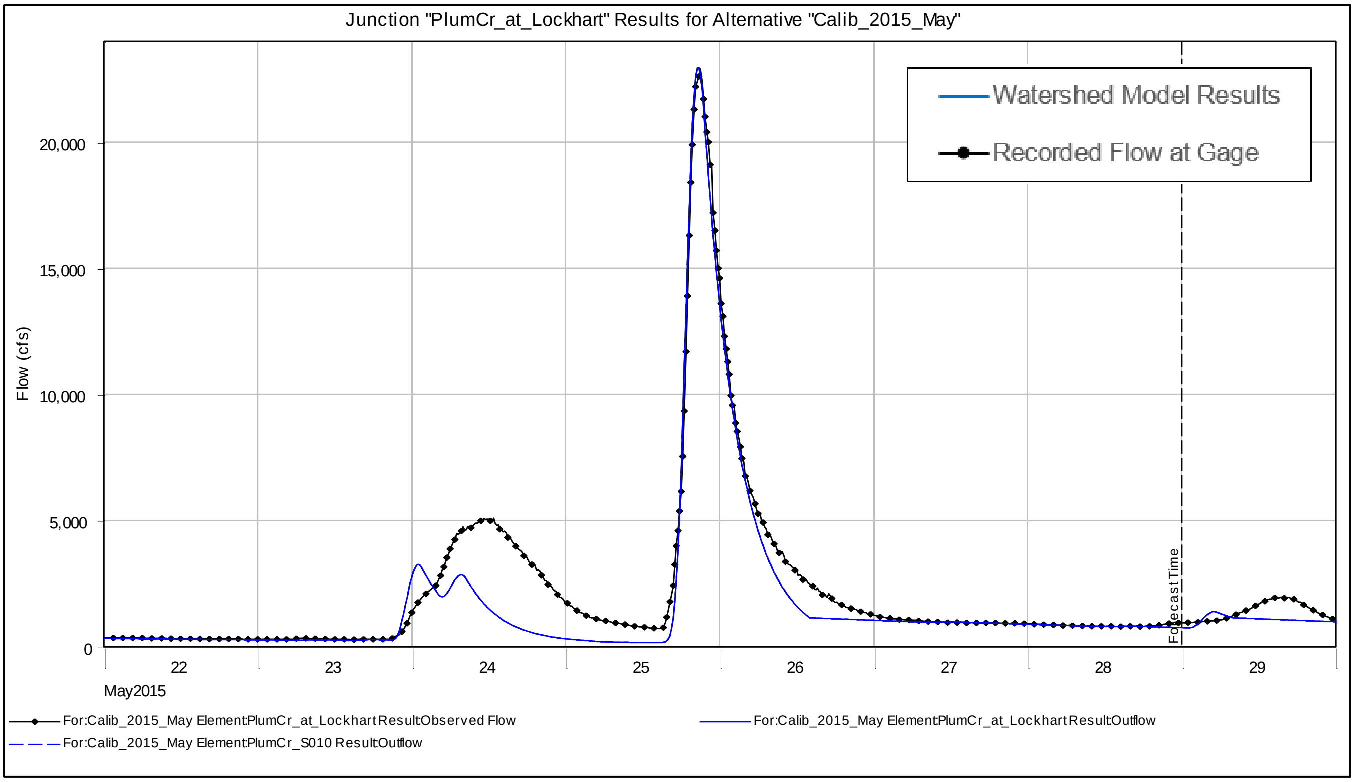

Figure 6.36: May 2015 Calibration Results for Plum Creek at Lockhart, TX

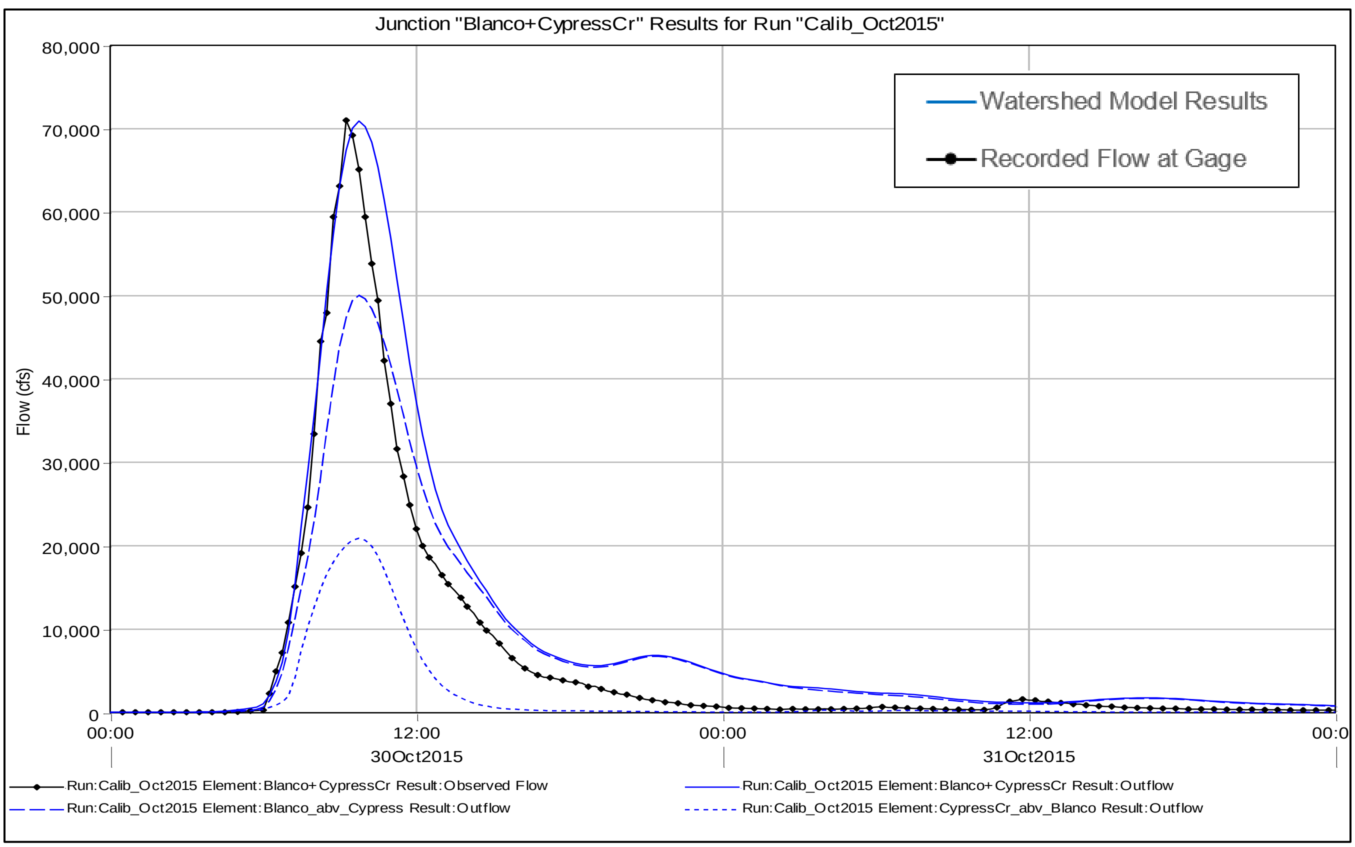

Figure 6.37: Oct 2015 Calibration Results for the Blanco River at Wimberley, TX

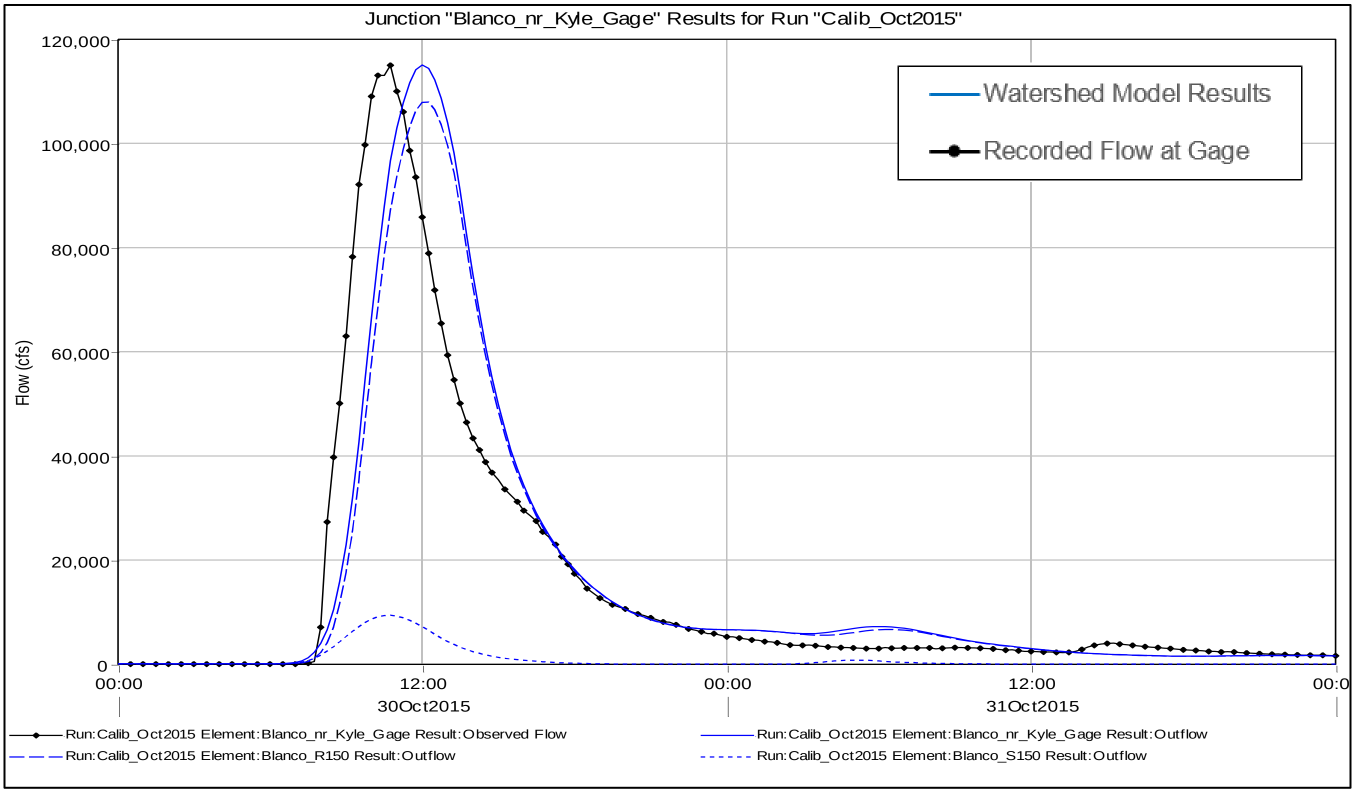

Figure 6.38: Oct 2015 Calibration Results for the Blanco River near Kyle, TX

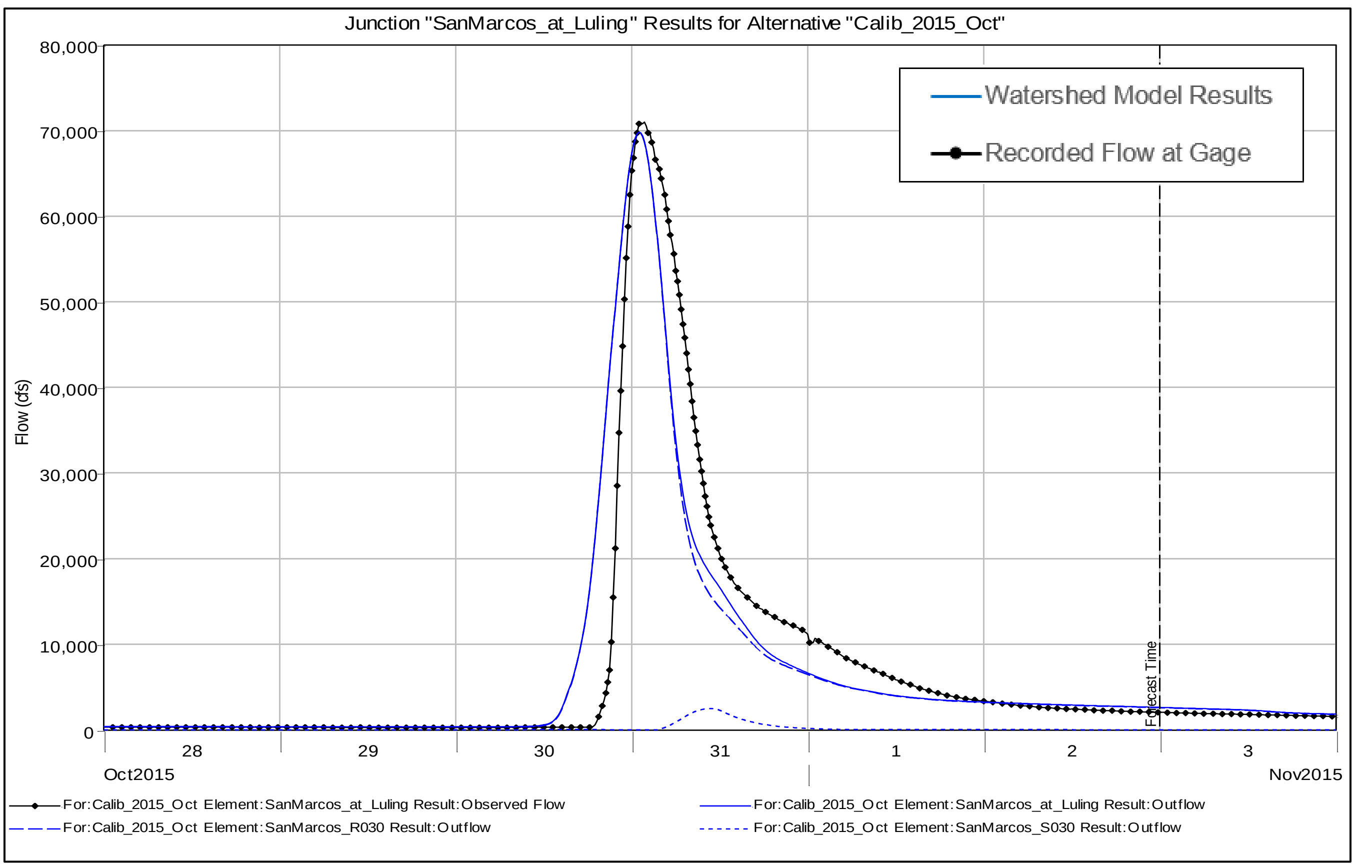

Figure 6.39: Oct 2015 Calibration Results for the San Marcos River at Luling, TX

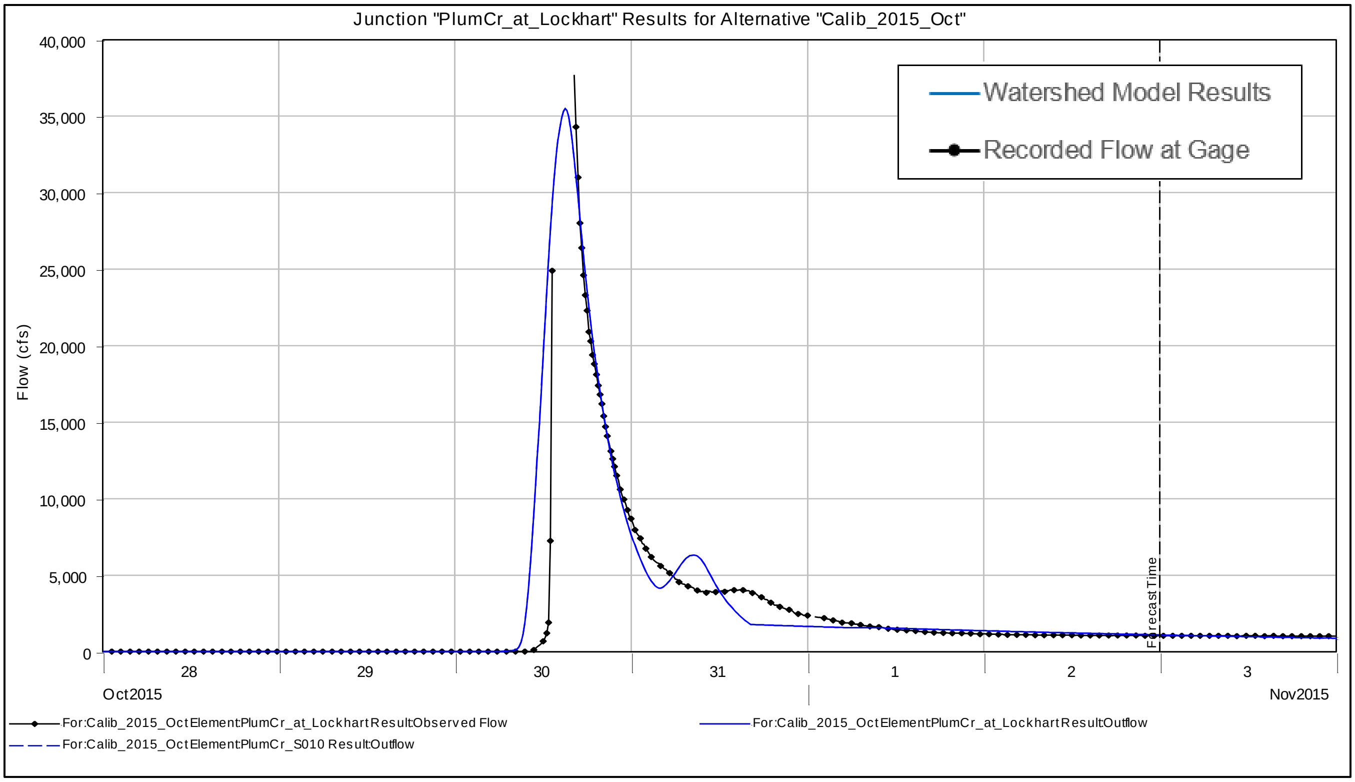

Figure 6.40: Oct 2015 Calibration Results for Plum Creek at Lockhart, TX

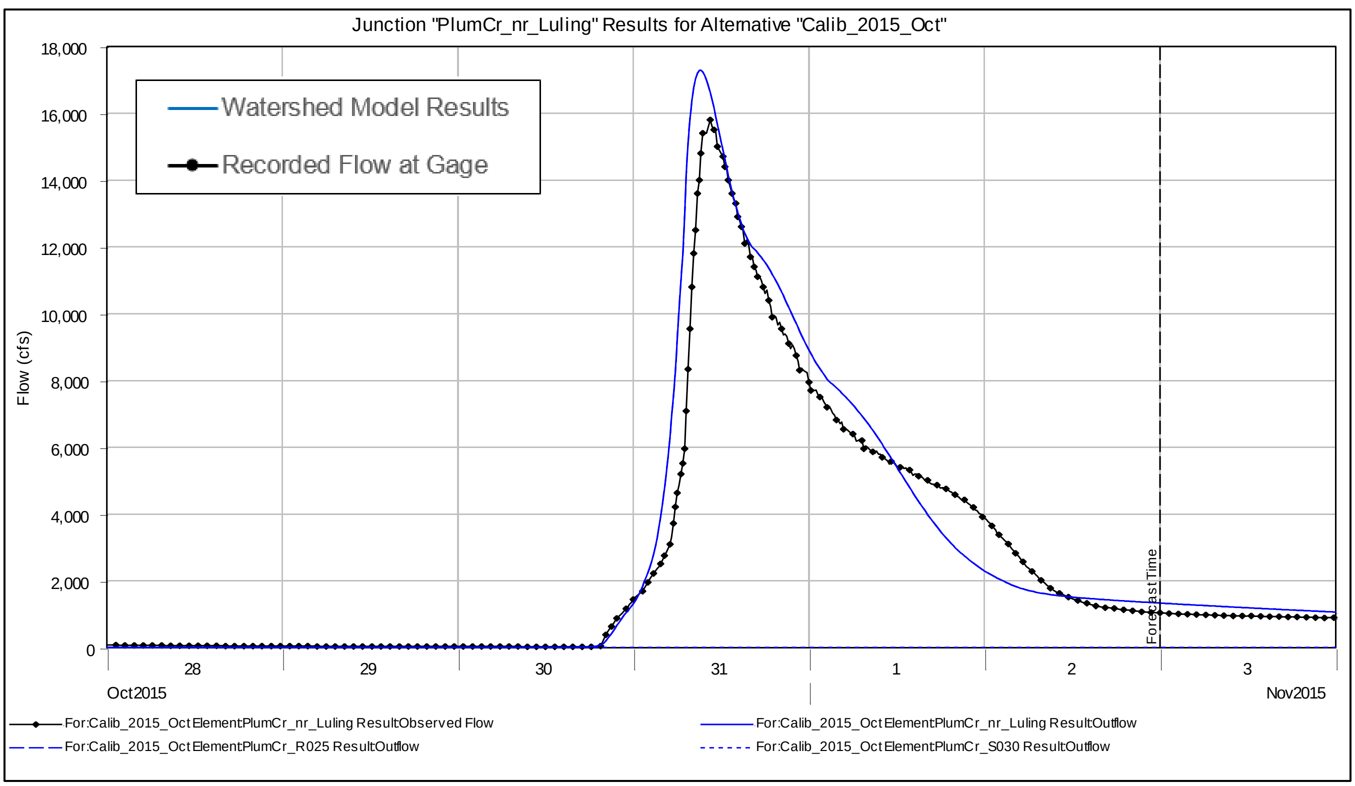

Figure 6.41: Oct 2015 Calibration Results for Plum Creek near Luling, TX

The area above the San Marcos gage received the least amount of calibration, which was primarily due to the lack of observed hydrograph data for flood events at that gage. The 2007 and 2012 events were the only events where the full observed hydrograph was available. These were not very large events over this watershed, and the computed shape for 2012 differed from the observed. The timing of the peaks matched well for both events suggesting a reasonable lag time estimate. Estimated peaks were available for the 1998 and 2004 calibration events. The gage did not record during either of the 2015 events flood events. This watershed has a drainage area of approximately 49 square miles and is about 90% controlled by NRCS detention structures upstream of the gage. NRCS Dams No. 1, 2 and 3 are modeled as reservoir elements inside of HEC-HMS.

The area above the Blanco River at Wimberley received the most calibration, as full or partial observed hydrographs were available for seven calibration storms, including the two large events in 2015. Calibration of this area revealed faster lag times than were initially estimated using the default equations. This is likely due to the steep terrain and narrow valleys upstream of Wimberley. The calibrations also indicated that during most observed events, the upper Blanco and the Little Blanco Rivers peak within one to two hours of each other. The combination of the hydrographs from those two rivers lead to rapidly rising hydrographs and large peak flows downstream of the confluence of the Blanco River with the Little Blanco River, as demonstrated by the May 2015 flood event. As seen in the above figures, the model was able to reproduce the peak flows, timing and shape of the observed hydrographs at Wimberely very well. This includes being able to reproduce the obseved flood of record at Wimberely, which occurred in May of 2015.

The calibration of the Blanco River near Kyle was more limited than that at Wimberley due to missing gage data. The stream gage at Kyle was washed out during three different flood events, and only peak flow estimates were available for those events. When observed hydrographs were available, the model did well at reproducing the shape and peak of the observed hydrograph. The exact timing of the peak at Kyle was sometimes difficult to match, particularly for the October 2015 event, due to the effects of the modified puls routing downstream of Wimberely. The volume of the November 2001 flow hydrograph at Kyle could not be calibrated. The USGS flow data for that event indicate that the volume of water that passed by the Wimberley gage was 8,000 acre-feet greater than the volume of water that passed by the Kyle gage. This is also in spite of the fact that over 7 inches of rain fell in between Wimberely and Kyle. The problem with the flow data for that event is likely due to inaccuracies in the USGS rating curves, but more flow measurements are needed in order to verify that. Therefore, the shape of the November 2001 observed flow hydograph at Kyle was calibrated, but the peak flow and volume were ignored.

The areas above the San Marcos at Luling and Plum Creek at Lockhart gages were well calibrated. Observed hydrographs for five significant events were available at those gages and were matched very well by the HEC-HMS model. For Plum Creek near Luling, full hydrographs were only available for two events, and an estimated peak flow was available for a third event. However, the model calibrated well to the observed flow data that was available. The October 2015 event in particular allowed for detailed calibration of the routing on Plum Creek in between Lockhart and Luling. This is because the rain for the October 2015 event fell almost entirely above Lockhart. The observed flow hydrographs at the gages indicate that the October 2015 peak flow was reduced from over 35,000 cfs at Lockhart to just over 17,000 cfs at Luling. Adjustments to the number of subreaches in the modified puls routing reaches upstream of Luling allowed the model to reproduce this level of attenuation very well.

6.5. Final Model Parameters

After the initial parameter estimates were made and the calibration process was completed, the final parameters were established. The final lag times and peaking coefficients were developed by taking a weighted average of the lag times and peaking coefficients from the calibration events. The volume of runoff from the subbasin for that event was used to weight the calibrated lag times. This method has the effect of granting a higher weight to the lag times that were calibrated from larger, more intense storms, and it ignores the storms that generated no runoff from a particular subbasin. During the calibration process, the use of lower peaking coefficients, which would lead to wider and flatter hydrographs, was tested against the observed downstream hydrographs at the gages. However, in most cases, the lower peaking coefficients had a strongly negative impact on the model’s ability to match the shape and peak value of the observed hydrographs. Lower peaking coefficients were used for Plum Creek above Lockhart and for York Creek because those subbasins contain a dense network of NRCS structures which provide a dampening effect on the peak flows. The final Snyder’s lag times and peaking coefficients are shown in Table 6.16.

The final baseflow parameters were selected based on the results of the calibration runs. Specifically, an initial flow per square mile was selected based on typical flow rates observed on each reach of the river, and the recession constant and ratio to peak were selected based on the slope and shape of the receding limb of the hydrograph at the downstream gages. One will also notice that significantly higher baseflow parameters were used for the SanMarcos_S005 and the CypressCr_BR_S020 subbasins. Those parameters were selected in order to mimic the observed flow from the springs in the upper San Marcos and Cypress Creek watersheds. The final baseflow parameters are also shown in Table 6.16.

The final Mod Puls storage discharge relationships were calculated from detailed steady flow HEC-RAS models, and the final number of subreaches were selected based on calibration to the observed attenuation of the flood hydrograph in between stream gages. The final routing subreach values are shown in Table 6.17.

In observed storm events, the initial and constant losses vary from storm to storm according to the antecedent moisture conditions of the soil. The losses for the frequency storms were developed using the USACE Fort Worth District Method for determining losses based on percent sand (Rodman, 1977). This method produces a different set of loss rates for each storm frequency. These losses also fall well within the band of observed losses from the calibration storms. The default initial and constant losses for the 2-yr through 25-yr storms were then adjusted for each given frequency in order to have a better correlation with the observed frequency curves estimated from the USGS gage records. This was done because of the increased confidence level in the statistical frequency curve for the 2 through 10-yr recurrence intervals. The 25-yr losses were adjusted to create a smooth transition between the 50-yr to the 10-yr values. The final loss rates used for each frequency storm event are given in Tables 6.18 and 6.19.

Table 6.16: Final Snyder's Transform and Baseflow Parameters

Subbasin Name	Lag Time (hr)	Peaking Coefficient	Initial Discharge (cfs / sq mi)	Recession Constant	Ratio to Peak
Blanco_S010	2.2	0.78	0.3	0.80	0.015
Blanco_S020	2.6	0.78	0.3	0.80	0.015
Blanco_S030	2.0	0.78	0.3	0.80	0.015
Blanco_S040	3.7	0.78	0.3	0.80	0.015
Blanco_S050	3.5	0.78	0.3	0.80	0.015
LittleBlanco_S010	2.2	0.78	0.3	0.80	0.015
LittleBlanco_S020	2.4	0.78	0.3	0.80	0.015
LittleBlanco_S030	2.7	0.78	0.3	0.80	0.015
LittleBlanco_S040	3.6	0.78	0.3	0.80	0.015
Blanco_S060	0.7	0.78	0.3	0.80	0.015
WanslowCr_BR_S010	2.7	0.78	0.3	0.80	0.015
Blanco_S070	2.3	0.78	0.3	0.80	0.015
Blanco_S080	2.0	0.78	0.3	0.80	0.015
CarpersCr_BR_S010	3.3	0.78	0.3	0.80	0.015
Blanco_S090	2.4	0.78	0.3	0.80	0.015
Blanco_S100	0.9	0.78	0.3	0.80	0.015
WilsonCr_BR_S010	1.9	0.78	0.3	0.80	0.015
Blanco_S110	0.8	0.78	0.3	0.80	0.015
CypressCr_BR_S010	2.2	0.78	0.3	0.80	0.015
CypressCr_BR_S020	1.9	0.78	0.8	0.95	0.03
CypressCr_BR_S030	2.2	0.78	0.3	0.80	0.015
Blanco_S120	1.8	0.72	0.2	0.80	0.007
Blanco_S130	2.5	0.72	0.2	0.80	0.007
LoneManCr_BR_S010	3.6	0.72	0.2	0.80	0.007
Blanco_S140	2.4	0.72	0.2	0.80	0.007
HalifaxCr_BR_S010	3.7	0.72	0.2	0.80	0.007
Blanco_S150	2.5	0.72	0.2	0.80	0.007
Blanco_S160	3.3	0.72	0.2	0.80	0.007
Blanco_S170	2.5	0.75	0.2	0.80	0.007
SinkCk_S010	4.4	0.7813	0.3	0.89	0.03
SinkCk_S020	3.4	0.7813	0.3	0.89	0.03
SinkCk_S030	1.9	0.7813	0.3	0.89	0.03
SinkCk_S040	2.3	0.7813	0.3	0.89	0.03
SanMarcos_S005	2.6	0.7813	15	0.99	0.03
SanMarcos_S008	1.4	0.7813	0.3	0.89	0.03
PurgatoryCr_S010	5.5	0.7813	0.3	0.80	0.02
SanMarcos_S010	1.9	0.75	0.25	0.80	0.02
SanMarcos_S020	6.8	0.75	0.25	0.80	0.02
YorkCr_S010	8.5	0.7	0.3	0.85	0.03
SanMarcos_S030	7.5	0.75	0.25	0.80	0.02
SanMarcos_S040	5.0	0.75	0.25	0.80	0.02
PlumCr_S010	4.9	0.5586	0.01	0.80	0.1
PlumCr_S020	7.4	0.7813	0.01	0.50	0.1
TenneyCr_S010	5.6	0.7813	0.01	0.50	0.1
PlumCr_S030	9.5	0.7813	0.01	0.50	0.1
PlumCr_S040	4.6	0.7813	0.3	0.79	0.1
SanMarcos_S050	13.0	0.7813	0.3	0.89	0.05

Table 6.17: Final Modified Puls Routing Parameters

HEC-HMS Reach Name	Storage-Discharge Model Source	No. Subreaches
Blanco_R020F	Hays Co FIS HEC-1	2
Blanco_R020H	Hays Co FIS HEC-1	3
Blanco_R030J	Hays Co FIS HEC-1	1
Blanco_R030L	Hays Co FIS HEC-1	2
Blanco_R030M	Hays Co FIS HEC-1	1
Blanco_R040O	Hays Co FIS HEC-1	2
Blanco_R040P	Hays Co FIS HEC-1	3
Blanco_R040R	Hays Co FIS HEC-1	5
Blanco_R050S	Hays Co FIS HEC-1	3
Blanco_R050T	Hays Co FIS HEC-1	5
LittleBlanco_R020V	Hays Co FIS HEC-1	2
LittleBlanco_R030W	Hays Co FIS HEC-1	3
LittleBlanco_R030X	Hays Co FIS HEC-1	3
LittleBlanco_R040Y	Hays Co FIS HEC-1	5
Blanco_R060Z	Hays Co FIS HEC-1	1
Blanco_R070	Blanco River HEC-RAS	5
Blanco_R080	Blanco River HEC-RAS	4
Blanco_R090	Blanco River HEC-RAS	4
Blanco_R100	Blanco River HEC-RAS	2
Blanco_R110	Blanco River HEC-RAS	1
CypressCr_R0204C	Hays Co FIS HEC-1	1
CypressCr_R0206C	Hays Co FIS HEC-1	1
CypressCr_R0206CL	Hays Co FIS HEC-1	1
CypressCr_R02010C	Hays Co FIS HEC-1	1
CypressCr_R03012C	Hays Co FIS HEC-1	1
CypressCr_R03014C	Hays Co FIS HEC-1	1
CypressCr_R03016C	Hays Co FIS HEC-1	1
Blanco_R120	Blanco River HEC-RAS	2
Blanco_R130	Blanco River HEC-RAS	5
Blanco_R140	Blanco River HEC-RAS	5
Blanco_R150	Blanco River HEC-RAS	4
Blanco_R160a	Blanco River HEC-RAS	1
Blanco_R160b	Blanco River HEC-RAS	2
Blanco_R170	Blanco River HEC-RAS	3
SinkCk_R010	Upper San Marcos HEC-RAS	1
SinkCk_R020	Upper San Marcos HEC-RAS	1
SinkCk_R030	Upper San Marcos HEC-RAS	1
SinkCk_R040	Upper San Marcos HEC-RAS	1
SinkCk_R050	Upper San Marcos HEC-RAS	1
SanMarcos_R003	Upper San Marcos HEC-RAS	1
SanMarcos_R005	Upper San Marcos HEC-RAS	1
SanMarcos_R007	Upper San Marcos HEC-RAS	1
SanMarcos_R020	San Marcos River HEC-RAS	8
SanMarcos_R030	San Marcos River HEC-RAS	5
SanMarcos_R040	San Marcos River HEC-RAS	1
PlumCr_R010	Plum Creek HEC-RAS	6
PlumCr_R020	Plum Creek HEC-RAS	3
SanMarcos_R050	San Marcos River HEC-RAS	3

Table 6.18: Final Initial and Constant Losses for the 2-yr through 25-yr Frequency Storms

	2-yr	2-yr	5-yr	5-yr	10-yr	10-yr	25-yr	25-yr
Subbasin Name	Initial (in)	Constant (in/hr)	Initial (in)	Constant (in/hr)	Initial (in)	Constant (in/hr)	Initial (in)	Constant (in/hr)
Blanco_S010	1.80	0.208	1.78	0.207	1.68	0.203	1.24	0.145
Blanco_S020	1.81	0.209	1.79	0.208	1.68	0.204	1.25	0.146
Blanco_S030	1.76	0.204	1.74	0.203	1.65	0.201	1.22	0.143
Blanco_S040	1.73	0.201	1.72	0.201	1.63	0.199	1.20	0.141
Blanco_S050	1.71	0.199	1.70	0.199	1.62	0.197	1.19	0.140
LittleBlanco_S010	1.82	0.210	1.79	0.208	1.69	0.204	1.25	0.146
LittleBlanco_S020	1.79	0.207	1.77	0.206	1.67	0.203	1.24	0.145
LittleBlanco_S030	1.72	0.200	1.71	0.200	1.63	0.198	1.20	0.141
LittleBlanco_S040	1.83	0.211	1.80	0.209	1.70	0.206	1.26	0.147
Blanco_S060	1.86	0.214	1.83	0.212	1.71	0.207	1.28	0.148
WanslowCr_BR_S010	1.86	0.214	1.82	0.211	1.71	0.207	1.27	0.148
Blanco_S070	1.84	0.212	1.81	0.210	1.70	0.206	1.27	0.147
Blanco_S080	1.82	0.210	1.80	0.209	1.69	0.205	1.26	0.146
CarpersCr_BR_S010	1.87	0.215	1.84	0.213	1.72	0.208	1.28	0.149
Blanco_S090	1.85	0.213	1.82	0.211	1.71	0.207	1.27	0.147
Blanco_S100	1.84	0.212	1.81	0.210	1.70	0.206	1.27	0.147
WilsonCr_BR_S010	1.87	0.215	1.83	0.212	1.72	0.208	1.28	0.148
Blanco_S110	1.85	0.213	1.82	0.211	1.71	0.206	1.27	0.147
CypressCr_BR_S010	1.86	0.214	1.83	0.212	1.72	0.207	1.28	0.148
CypressCr_BR_S020	1.87	0.215	1.83	0.212	1.72	0.208	1.28	0.148
CypressCr_BR_S030	1.85	0.213	1.82	0.211	1.71	0.207	1.27	0.148
Blanco_S120	1.86	0.214	1.83	0.212	1.72	0.208	1.28	0.148
Blanco_S130	1.87	0.215	1.84	0.213	1.72	0.208	1.28	0.149
LoneManCr_BR_S010	1.90	0.218	1.86	0.215	1.74	0.210	1.30	0.150
Blanco_S140	1.86	0.214	1.83	0.212	1.71	0.207	1.28	0.148
HalifaxCr_BR_S010	1.78	0.206	1.76	0.205	1.66	0.202	1.23	0.144
Blanco_S150	1.79	0.207	1.77	0.206	1.67	0.203	1.23	0.144
Blanco_S160	1.75	0.203	1.73	0.202	1.64	0.200	1.21	0.142
Blanco_S170	1.90	0.218	1.86	0.215	1.74	0.210	1.30	0.150
SinkCk_S010	2.48	0.330	2.41	0.300	2.07	0.260	1.37	0.170
SinkCk_S020	2.48	0.330	2.41	0.300	2.07	0.260	1.37	0.170
SinkCk_S030	2.48	0.330	2.41	0.300	2.07	0.260	1.37	0.170
SinkCk_S040	2.48	0.330	2.41	0.300	2.07	0.260	1.37	0.170
SanMarcos_S005	2.48	0.330	2.41	0.300	2.07	0.260	1.37	0.170
SanMarcos_S008	2.48	0.330	2.41	0.300	2.07	0.260	1.37	0.170
PurgatoryCr_S010	1.40	0.190	1.22	0.150	1.16	0.140	0.99	0.120
SanMarcos_S010	1.47	0.190	1.27	0.150	1.20	0.150	1.03	0.130
SanMarcos_S020	1.52	0.200	1.31	0.160	1.24	0.150	1.06	0.130
YorkCr_S010	1.88	0.270	1.78	0.220	1.70	0.210	1.44	0.180
SanMarcos_S030	1.58	0.200	1.36	0.160	1.28	0.160	1.10	0.130
SanMarcos_S040	1.68	0.210	1.45	0.170	1.36	0.160	1.17	0.140
PlumCr_S010	2.00	0.19	2.00	0.19	1.80	0.14	0.98	0.120
PlumCr_S020	1.46	0.190	1.19	0.140	1.08	0.130	0.92	0.110
TenneyCr_S010	1.63	0.210	1.32	0.160	1.18	0.140	1.02	0.120
PlumCr_S030	1.49	0.190	1.21	0.150	1.09	0.140	0.93	0.110
PlumCr_S040	1.61	0.210	1.31	0.160	1.17	0.140	1.01	0.120
SanMarcos_S050	1.71	0.220	1.47	0.170	1.37	0.170	1.18	0.140

Table 6.19: Final Initial and Constant Losses for the 50-yr through 500-yr Frequency Storms

	50-yr	50-yr	100-yr	100-yr	250-yr	250-yr	500-yr	500-yr
Subbasin Name	Initial (in)	Constant (in/hr)	Initial (in)	Constant (in/hr)	Initial (in)	Constant (in/hr)	Initial (in)	Constant (in/hr)
Blanco_S010	1.06	0.125	0.87	0.095	0.71	0.084	0.58	0.075
Blanco_S020	1.06	0.126	0.88	0.096	0.71	0.084	0.59	0.076
Blanco_S030	1.04	0.123	0.86	0.093	0.70	0.082	0.58	0.073
Blanco_S040	1.03	0.121	0.86	0.091	0.69	0.080	0.57	0.071
Blanco_S050	1.02	0.120	0.85	0.090	0.69	0.079	0.57	0.070
LittleBlanco_S010	1.06	0.126	0.88	0.096	0.71	0.084	0.59	0.076
LittleBlanco_S020	1.05	0.125	0.87	0.095	0.71	0.083	0.58	0.075
LittleBlanco_S030	1.02	0.121	0.86	0.091	0.69	0.080	0.57	0.071
LittleBlanco_S040	1.07	0.127	0.88	0.097	0.72	0.085	0.59	0.077
Blanco_S060	1.08	0.128	0.89	0.098	0.72	0.087	0.59	0.078
WanslowCr_BR_S010	1.08	0.128	0.89	0.098	0.72	0.086	0.59	0.078
Blanco_S070	1.07	0.127	0.89	0.097	0.72	0.086	0.59	0.077
Blanco_S080	1.07	0.126	0.88	0.096	0.71	0.085	0.59	0.076
CarpersCr_BR_S010	1.09	0.129	0.89	0.099	0.72	0.087	0.60	0.079
Blanco_S090	1.08	0.127	0.89	0.097	0.72	0.086	0.59	0.077
Blanco_S100	1.07	0.127	0.89	0.097	0.72	0.086	0.59	0.077
WilsonCr_BR_S010	1.08	0.128	0.89	0.098	0.72	0.087	0.59	0.078
Blanco_S110	1.08	0.127	0.89	0.097	0.72	0.086	0.59	0.077
CypressCr_BR_S010	1.08	0.128	0.89	0.098	0.72	0.087	0.59	0.078
CypressCr_BR_S020	1.09	0.128	0.89	0.098	0.72	0.087	0.59	0.078
CypressCr_BR_S030	1.08	0.128	0.89	0.098	0.72	0.086	0.59	0.078
Blanco_S120	1.08	0.128	0.89	0.098	0.72	0.087	0.59	0.078
Blanco_S130	1.09	0.129	0.89	0.099	0.72	0.087	0.60	0.079
LoneManCr_BR_S010	1.10	0.130	0.90	0.100	0.73	0.088	0.60	0.080
Blanco_S140	1.08	0.128	0.89	0.098	0.72	0.087	0.59	0.078
HalifaxCr_BR_S010	1.05	0.124	0.87	0.094	0.70	0.083	0.58	0.074
Blanco_S150	1.05	0.124	0.87	0.094	0.71	0.083	0.58	0.074
Blanco_S160	1.03	0.122	0.86	0.092	0.70	0.081	0.57	0.072
Blanco_S170	1.10	0.130	0.90	0.100	0.73	0.089	0.60	0.080
SinkCk_S010	0.86	0.100	0.76	0.070	0.61	0.060	0.51	0.050
SinkCk_S020	0.86	0.100	0.76	0.070	0.61	0.060	0.51	0.050
SinkCk_S030	0.86	0.100	0.76	0.070	0.61	0.060	0.51	0.050
SinkCk_S040	0.86	0.100	0.76	0.070	0.61	0.060	0.51	0.050
SanMarcos_S005	0.86	0.100	0.76	0.070	0.61	0.060	0.51	0.050
SanMarcos_S008	0.86	0.100	0.76	0.070	0.61	0.060	0.51	0.050
PurgatoryCr_S010	0.87	0.100	0.77	0.070	0.61	0.060	0.51	0.050
SanMarcos_S010	0.90	0.110	0.78	0.080	0.63	0.060	0.52	0.060
SanMarcos_S020	0.92	0.110	0.8	0.080	0.64	0.070	0.53	0.060
YorkCr_S010	1.27	0.150	1.14	0.110	0.92	0.090	0.75	0.080
SanMarcos_S030	0.95	0.110	0.81	0.080	0.65	0.070	0.54	0.060
SanMarcos_S040	1.00	0.120	0.84	0.090	0.68	0.080	0.56	0.070
PlumCr_S010	0.82	0.100	0.76	0.070	0.61	0.060	0.51	0.050
PlumCr_S020	0.85	0.100	0.78	0.080	0.63	0.060	0.52	0.060
TenneyCr_S010	0.92	0.110	0.83	0.090	0.66	0.070	0.55	0.070
PlumCr_S030	0.86	0.100	0.79	0.080	0.63	0.070	0.53	0.060
PlumCr_S040	0.92	0.110	0.82	0.080	0.66	0.070	0.55	0.060
SanMarcos_S050	1.01	0.120	0.85	0.090	0.68	0.080	0.57	0.070

6.6. Point Rainfall Depths for the Frequency Storms

As discussed in chapter 4, frequency point rainfall depths of various durations and recurrence intervals were collected for the Blanco and San Marcos River basins from the 2004 Atlas of DDF of precipitation for Texas published by the USGS (Asquith, 2004). The point rainfall depths for the Blanco River subbasins were taken from a point near Wimberley, Texas, as shown in Table 6.20. The point rainfall depths for the rest of the San Marcos subbasins were taken from a point near the lower basin's centroid, as shown in Table 6.21. These also happened to be the same point rainfall depths as were used in the Lower Guadalupe Feasibility Study.

Table 6.20: Frequency Point Rainfall Depths (inches) for the Blanco River Basin

Duration	Recurrence Interval							
	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	250-yr	500-yr
15min	1.00	1.24	1.41	1.75	2.00	2.25	2.65	2.95
1hr	1.74	2.30	2.70	3.25	3.80	4.33	5.20	5.90
2hr	2.20	2.90	3.42	4.10	4.80	5.60	6.60	7.60
3hr	2.40	3.18	3.75	4.55	5.30	6.20	7.40	8.60
6hr	2.73	3.67	4.27	5.20	6.10	7.10	8.60	10.00
12hr	3.08	4.10	4.90	6.00	7.00	8.20	10.00	11.90
24 hr	3.70	5.10	6.18	7.60	8.80	10.10	12.10	14.00

Table 6.21: Frequency Point Rainfall Depths (inches) for the San Marcos River Basin

Duration	Recurrence Interval							
	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	250-yr	500-yr
15min	1.07	1.41	1.66	2.02	2.33	2.69	3.23	3.71
1hr	1.83	2.41	2.82	3.41	3.9	4.45	5.29	6.01
2hr	2.3	3.07	3.61	4.39	5.06	5.8	6.94	7.93
3hr	2.41	3.29	3.94	4.87	5.68	6.59	8	9.25
6hr	2.73	3.68	4.38	5.39	6.27	7.27	8.82	10.2
12hr	3.14	4.26	5.08	6.27	7.31	8.49	10.32	11.95
24 hr	3.6	5.1	6.18	7.67	8.9	10.23	12.15	13.75

Both sets of frequency precipitation depths were utilized as point rainfall depths in the frequency storms for the final HEC-HMS rainfall-runoff model. The final frequency results were computed in HEC-HMS through the depth-area analysis of the applied frequency storms.

6.7. Frequency Storm Results

The frequency flow values were then calculated in HEC-HMS by applying the frequency rainfall depths to the final watershed model through a depth-area analysis. The calculated 1% annual chance (100-yr) peak discharges at the Wimberley and Kyle gages on the Blanco River were 152,600 and 153,900 cfs, respectively. The 1% annual chance (100-yr) peak discharges for the San Marcos River at San Marcos and Luling were 7,860 cfs and 142,400 cfs, respectively, and for Plum Creek, the 1% annual chance (100-yr) peak discharges were 48,900 cfs and 78,600 cfs at Lockhart and Luling, respectively. The final HEC-HMS frequency flows for significant locations throughout the watershed model can be seen in Table 6.22.

In some cases, one may observe that the simulated discharge decreases in the downstream direction. It is not an uncommon phenomenon to see decreasing frequency peak discharges for some river reaches as flood waters spread out into the floodplain and the hydrograph becomes dampened as it moves downstream. This can be due to a combination of peak attenuation due to river routing as well as the difference in timing between the peak of the main stem river versus the runoff from the local tributaries and subbasins.

Table 6.22: Summary of Discharges Results from HEC-HMS

Location Description	50%	20%	10%	4%	2%	1%	0.40%	0.20%
	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	250-YR	500-YR
Blanco River below Little Blanco	9,100	31,800	51,900	86,500	111,800	141,300	178,700	213,300
Blanco River at Wimberley	8,900	31,000	51,600	88,600	116,600	152,600	196,800	238,500
Blanco River near Kyle	8,600	30,300	50,700	88,100	116,300	153,900	199,300	244,900
Blanco River above San Marcos River	7,900	28,300	46,000	79,000	106,300	142,900	188,300	232,800
San Marcos River at San Marcos	310	1,380	2,530	4,100	5,160	7,860	14,800	21,100
San Marcos River below Purgatory Cr	950	2,720	6,640	12,000	17,200	23,100	31,400	40,300
San Marcos River above Blanco River	2,640	5,210	7,000	11,800	17,200	23,500	32,300	40,900
San Marcos River below Blanco River	8,800	29,900	48,500	82,400	110,500	153,600	205,500	255,900
San Marcos River above York Creek	8,400	27,600	45,800	75,900	100,200	136,500	182,200	237,900
San Marcos River below York Creek	8,800	29,400	49,000	80,100	105,500	144,100	194,000	257,100
San Marcos River at Luling	10,400	28,300	47,400	78,400	103,900	142,400	193,100	253,100
San Marcos River above Plum Creek	10,100	27,300	44,800	74,200	100,600	138,300	185,400	241,300
San Marcos River below Plum Creek	16,700	42,600	65,900	101,700	139,100	189,200	252,300	331,700
San Marcos Riv above Guadalupe R	13,900	38,000	56,700	91,000	128,000	178,200	239,700	304,600
Plum Creek at Lockhart	3,830	12,200	20,600	32,200	39,800	48,900	60,900	71,600
Plum Creek above Tenney Creek	5,700	13,900	18,800	26,200	39,200	53,900	74,400	91,400
Plum Creek below Tenney Creek	7,500	19,700	27,100	37,600	46,200	61,000	85,400	105,600
Plum Creek near Luling	6,600	17,700	29,600	45,900	60,600	78,600	106,300	132,100
Plum Creek above San Marcos River	6,800	18,300	30,600	47,200	62,300	80,700	108,900	135,100
Below SCS Dam No. 5	800	2,900	6,700	11,800	15,800	20,300	26,000	30,700
York Creek above San Marcos River	3,600	12,000	18,000	27,400	35,400	45,500	58,900	70,000

7.0 Comparison of Frequency Flow Estimates

After completing the analyses by the two different methods, their results were compared in terms of frequency discharge estimates at the USGS stream gages. These comparative frequency flow estimates are given in Tables 7.1 to 7.6. Figures 7.1 through 7.6 plot the estimated frequency curves at each gage along with their confidence limits and the previous published discharges from the effective FEMA Flood Insurance Studies (FIS) (FEMA, 2005).

Table 7.1: Frequency Flow Results Comparison for the Blanco River at Wimberley, TX

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA Flow**	2016 Statistical Analysis	Rainfall-Runoff Model
0.002	500	203,800	269,400	238,500
0.004	250*		199,300	196,800
0.01	100	112,800	153,700	152,600
0.02	50	86,200	114,400	116,600
0.04	25		81,200	88,600
0.1	10	36,800	46,400	51,600
0.2	5		26,500	31,000
0.5	2		8,280	8,900

*Statistical analysis reports 200-yr return period

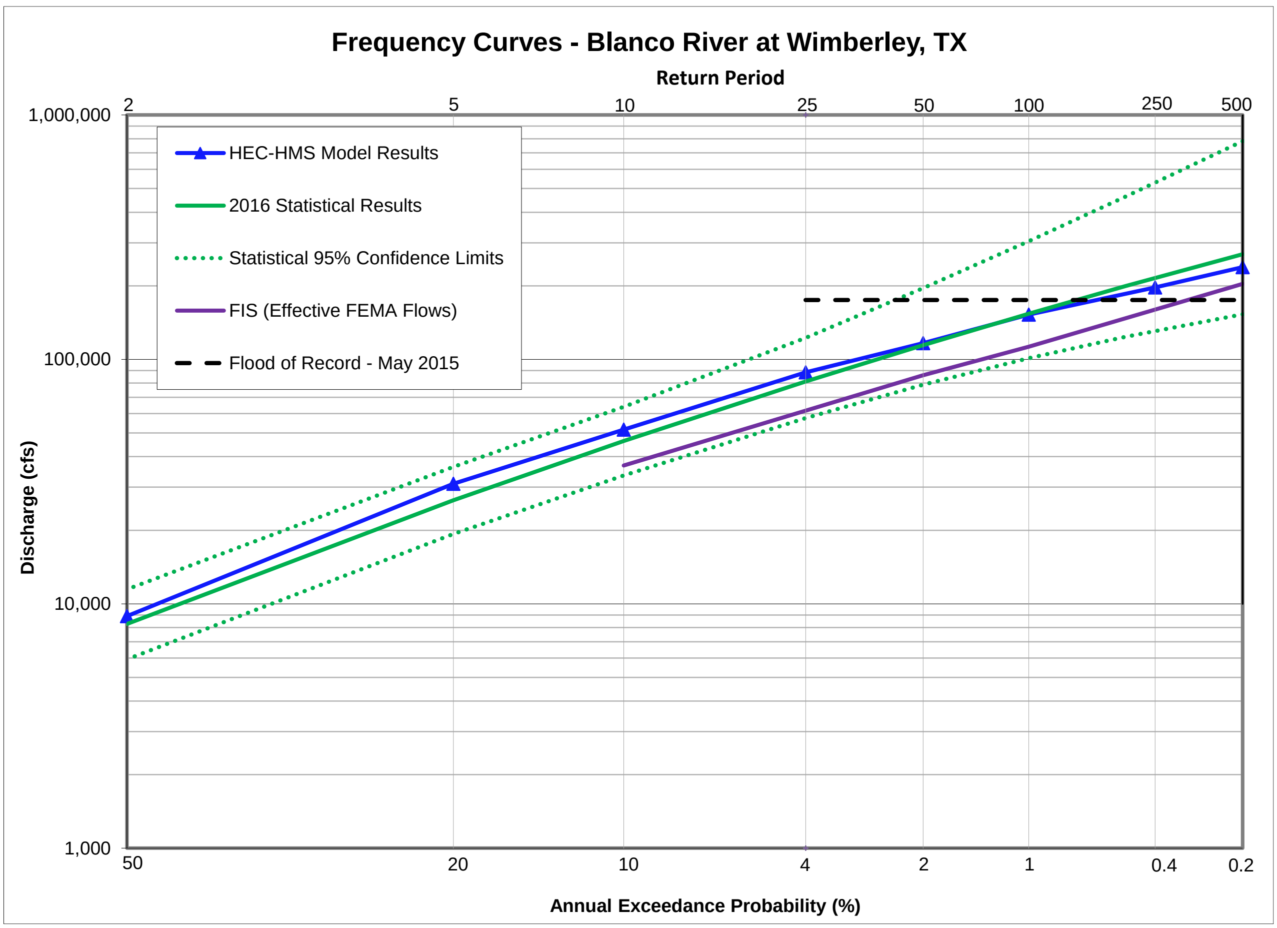

Figure 7.1: Flow Frequency Curve Comparison for the Blanco River at Wimberley, TX

Table 7.2: Frequency Flow Results Comparison for the Blanco River near Kyle, TX

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS Flow	2016 Statistical Analysis	Rainfall-Runoff Model
0.002	500	219,100	271,100	244,900
0.004	250*		212,500	199,300
0.01	100	122,600	170,400	153,900
0.02	50	93,900	131,100	116,300
0.04	25		95,290	88,100
0.1	10	40,600	54,810	50,700
0.2	5		30,450	30,300
0.5	2		8,110	8,600

*Statistical analysis reports 200-yr return period

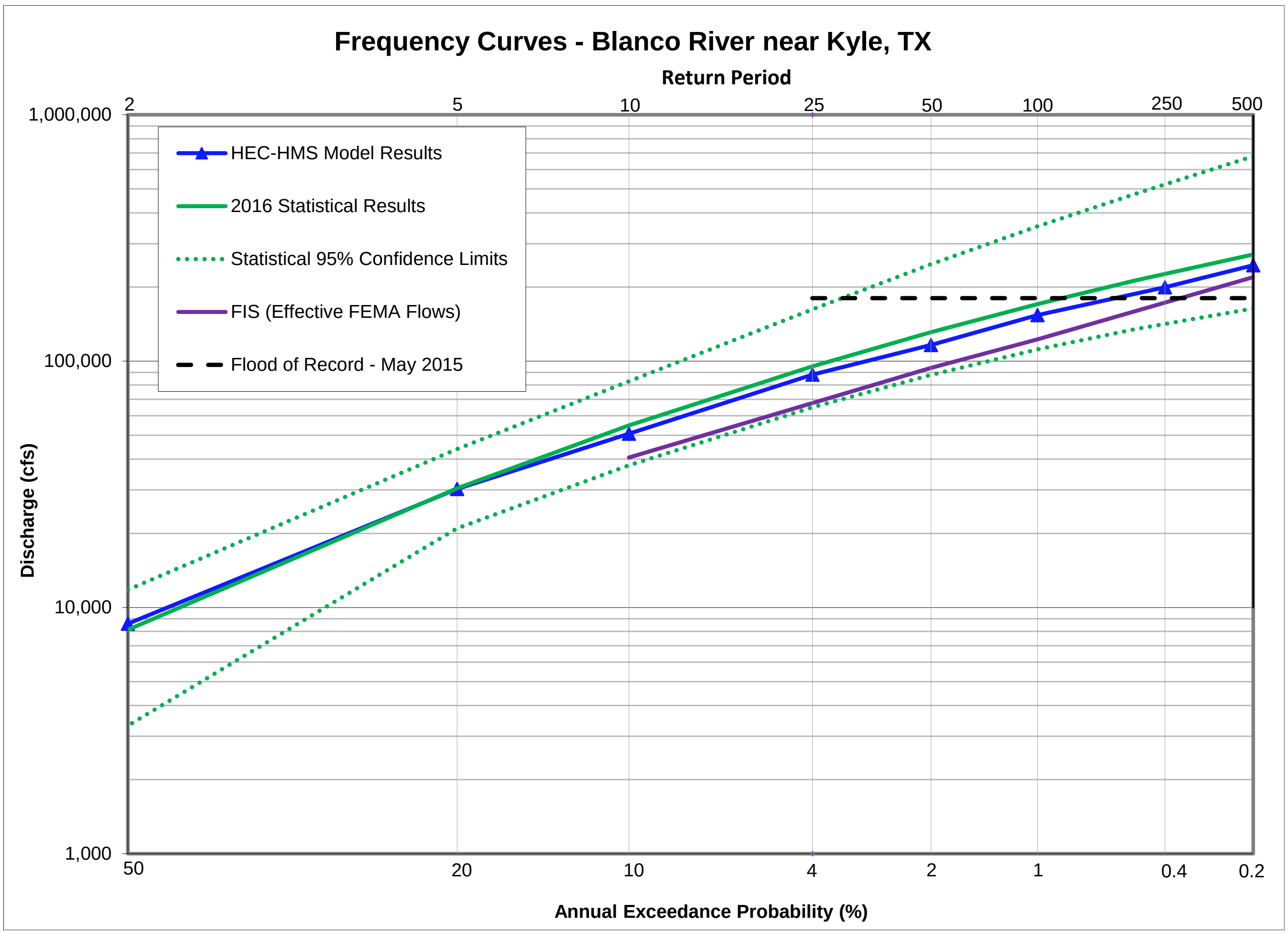

Figure 7.2: Flow Frequency Curve Comparison for the Blanco River near Kyle, TX

Table 7.3: Frequency Flow Results Comparison for the San Marcos River at San Marcos, TX

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS Flow	2016 Statistical Analysis	Rainfall-Runoff Model
0.002	500	20,290	139,700	21,100
0.004	250*		57,140	14,800
0.01	100	7,660	28,980	7,860
0.02	50	6,220	14,650	5,160
0.04	25		7,370	4,100
0.1	10	3,680	2,940	2,530
0.2	5		1,450	1,380
0.5	2		550	310

*Statistical analysis reports 200-yr return period

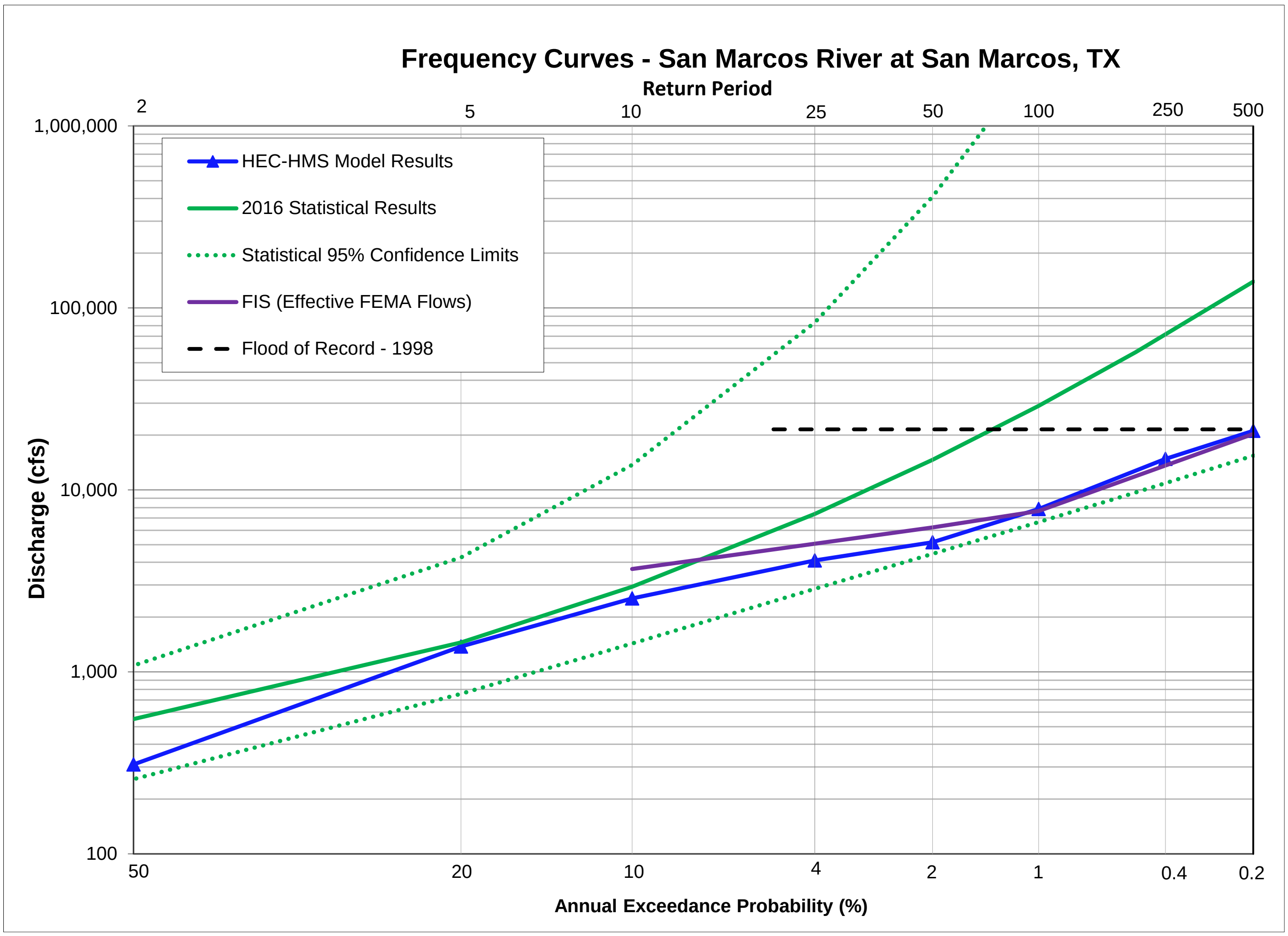

Figure 7.3: Flow Frequency Curve Comparison for the San Marcos River at San Marcos, TX

Table 7.4: Frequency Flow Results Comparison for the San Marcos River at Luling, TX

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS Flow	2016 Statistical Analysis	Rainfall-Runoff Model
0.002	500	183,000	253,500	253,100
0.004	250*		186,100	193,100
0.01	100	110,000	143,600	142,400
0.02	50	85,100	107,600	103,900
0.04	25		77,500	78,400
0.1	10	40,000	46,100	47,400
0.2	5		27,900	28,300
0.5	2		10,250	10,400

*Statistical analysis reports 200-yr return period

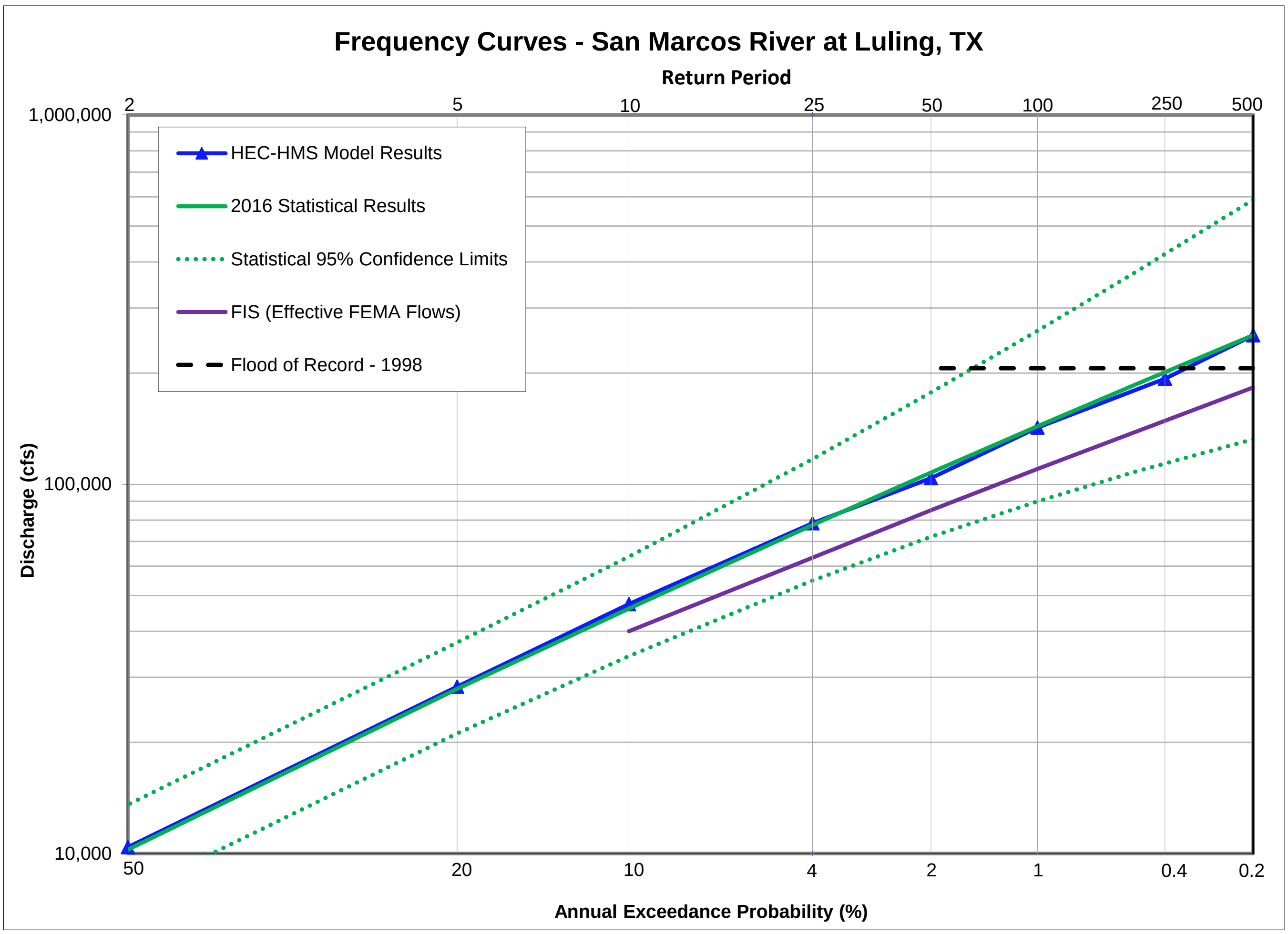

Figure 7.4: Flow Frequency Curve Comparison for the San Marcos River at Luling, TX

Table 7.5: Frequency Flow Results Comparison for Plum Creek at Lockhart, TX

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS Flow	2016 Statistical Analysis	Rainfall-Runoff Model
0.002	500		98,000	71,600
0.004	250*		75,100	60,900
0.01	100		59,600	48,900
0.02	50		45,700	39,800
0.04	25		33,500	32,200
0.1	10		20,000	20,600
0.2	5		11,850	12,200
0.5	2		3,920	3,830

*Statistical analysis reports 200-yr return period

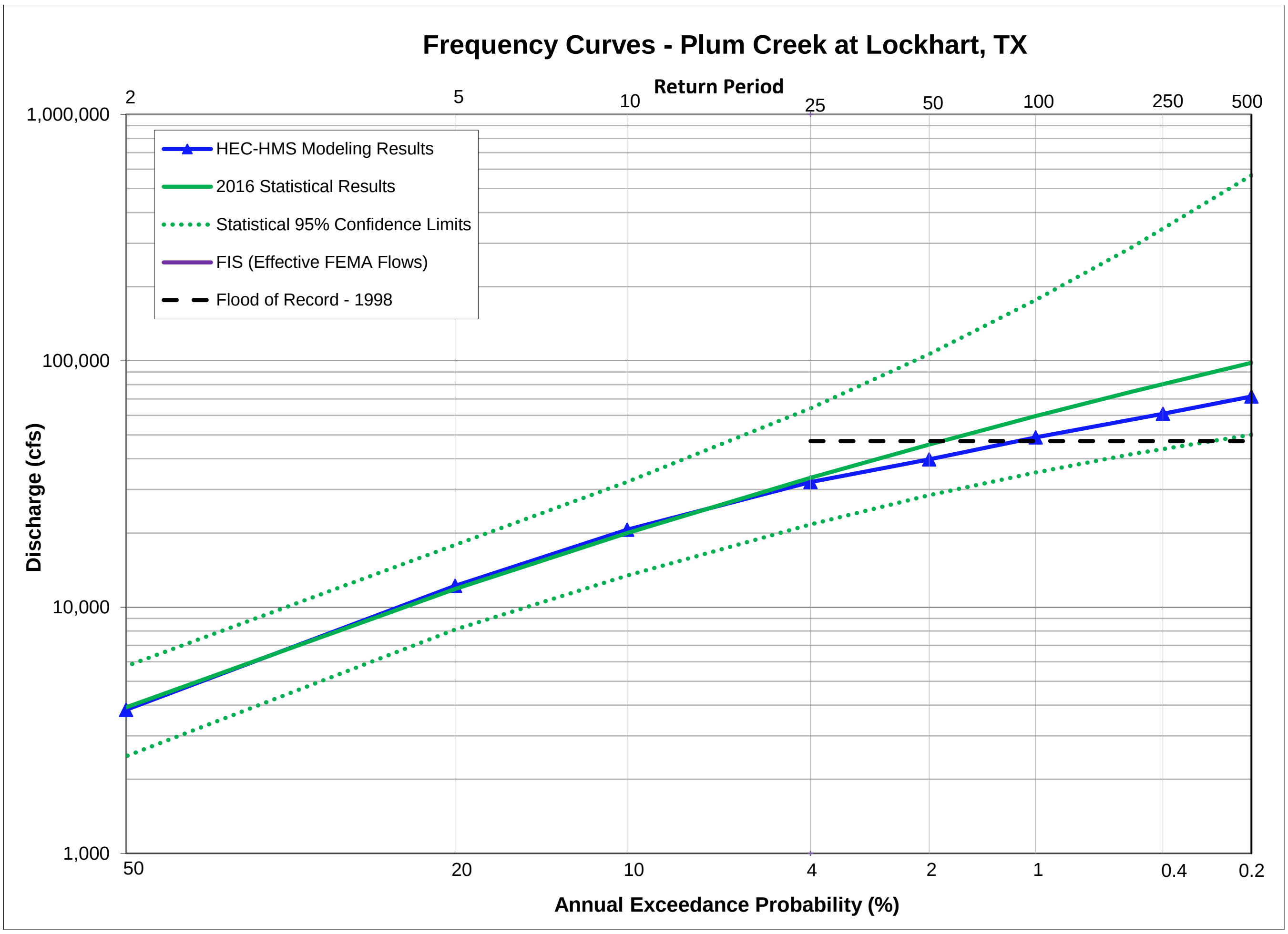

Figure 7.5: Flow Frequency Curve Comparison for the Plum Creek near Luling, TX

Table 7.6: Frequency Flow Results Comparison for Plum Creek near Luling, TX

Annual Exceedance Probability (AEP)	Return Period (years)	Currently Effective FEMA FIS Flow	2016 Statistical Analysis	Rainfall-Runoff Model
0.002	500		102,600	132,100
0.004	250*		85,400	106,300
0.01	100		72,500	78,600
0.02	50		59,600	60,600
0.04	25		46,850	45,900
0.1	10		30,600	29,600
0.2	5		19,200	17,700
0.5	2		6,370	6,600

*Statistical analysis reports 200-yr return period

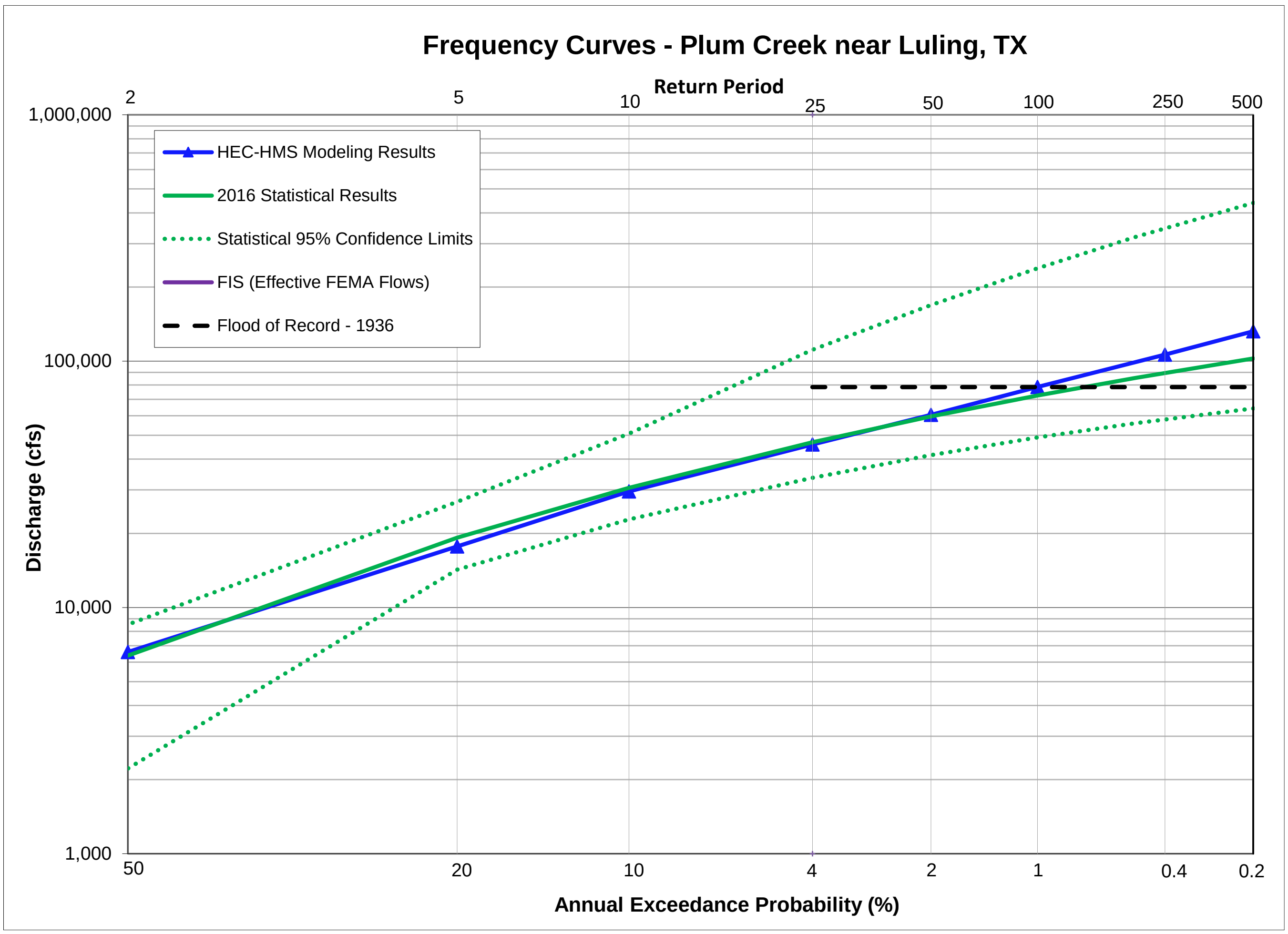

Figure 7.6: Flow Frequency Curve Comparison for the Plum Creek near Luling, TX

From these figures, one can see that with the exception of San Marcos River at San Marcos, the results of the statistical analysis and the HEC-MHS watershed model showed very good agreement with each other. Both sets of results were also significantly higher than the flows on the currently effective FEMA Flood Insurance Studies (FIS) (FEMA, 2005), which were based on regression equations at most of these locations. This is not surprising since the regression equations for this area tended to underestimate the 1% annual chance (100-yr) flow values due to the limited period of record that was available during the early 1990s which did not include the major flood events between 1998 and 2015, as discussed in section 2.4.

For the Blanco River at Wimberley and near Kyle and the San Marcos River at Luling, the watershed modeling and the statistical results showed a high degree of agreement with each other. However, the watershed modeling results were slightly lower than the 2016 statistical results at the 1% annual chance (100-yr) frequency. However, as illustrated by the change over time plots in section 5.4, the statistical estimates of the 1% annual chance (100-yr) continue to vary as each new year of data is added to the record.

For the San Marcos River at San Marcos, there is a great degree of separation between the statistical and modeling results. However, the statistical results at this location are based on only 21 years of record (1995 to2016). This is a relatively short period of record, which yields a low degree of confidence in the 1% annual chance (100-yr) statistical estimate. The gage record is also dominated by one large flood event (1998) which produced a peak of 21,500 cfs at the gage, as shown previously on Figure 5.10. The rest of the recorded annual peaks are much lower in magnitude, at less than 3,000 cfs. The HEC-HMS model estimates a 1% annual chance (100-yr) discharge that is significantly lower that the statistical analysis, at 7,860 cfs. This estimate is very similar to the effective FIS discharge, which was also based on a watershed model at this location. The modeling estimate is largely influenced by the effects of the three NRCS dams upstream of the gage which control over 90% of the drainage area at this location. Therefore, the watershed model is believed to provide a better representation of the physical processes in the watershed at this location.

For the Plum Creek gage at Lockhart, there is good agreement between the modeling and the statistical results. However, at the 1% annual chance (100-yr) frequency, the modeling results are lower than the statistical results at Lockhart. Once again, the peak flows at Lockhart are influenced by the presence of about 20 NRCS dams that control about 60% of the drainage area above Lockhart. These 20 dams were not modeled in detail in HEC-HMS, but they were accounted for in the calibration of the loss rates, peaking coefficients and lag times. The statistical estimate at this gage is based on a fairly long period of record (57 years), dating back to 1959. The flood of record at Lockhart occurred in October 1998, with a peak discharge of 47,200 cfs. The plotting positions of the statistical analysis would place that event at approximately a 50 to 60-yr frequency based on its 57 years of record. However, the basin average rainfall totals upstream Lockhart would indicate that the October 1998 storm was likely a less frequent event than the statistics would imply. The HEC-HMS model calibration showed that the 1998 storm generated approximately 10-inches of runoff at the Lockhart gage, which is on the order of a 1% annual chance (100-yr) rainfall. Likewise, the model's frequency curve results place the 1998 storm at closer to a 1% annual chance (100-yr) at Lockhart. Therefore, the watershed model is believe to provide a better estimate of the 1% annual chance (100-yr) discharge at Lockhart.

For the Plum Creek gage near Luling, there is good agreement between the modeling and the statistical results, and there is a fairly high degree of confidence in both sets of results for this location. However, at the 1% annual chance (100-yr) frequency, the modeling results are slightly higher than the statistical results at Luling. The statistical estimate at this gage is based on a fairly long period of record, dating back to 1930 at Luling, but as shown previously in Figure 5.20, the exact statistical estimate at Luling continues to vary from year to year with each new peak that is added to the record. One point of weakness in the statistical data at Luling is the fact that the gage was not in service during what was likely the flood of record at that location. The October 1998 flood event is believed to be the flood of record at Luling, which occurred during the seven year period (1994 to 2000) that the Plum Creek near Luling gage was not in service. The statistical curve does include an interval estimate of what the 1998 peak might have been, as shown in the highest green vertical lines on Figures 5.16 and 5.17, but those estimates are plotted with a large range of uncertainty. The calibrated HEC-HMS model reproduced the observed hydrographs well at Luling, and the upstream routing in between the Lockhart and Luling gages was also well calibrated to the observed attenuation between those gages during the October 2015 event.

8.0 Frequency Flow Recommendations

After reviewing of all of the above hydrologic information and analyses, the HEC-HMS watershed model discharges were recommended for adoption in the final results, as shown in Table 8.1 below. One reason for this decision was the tendency of the statistical results to change after each significant flood event, as demonstrated in the change over time plots in section 5.4. Statistical analyses, while informative, are still dependent on the observed sample of events, which inherently changes with each passing year. In addition, climate variability from wet to dry may result in non-representative samples in the gage record. Watershed modeling, on the other hand, is based on physical watershed characteristics, such as drainage area and stream slope, that do not tend to change as much over time. Climate variability can also be accounted for in the watershed model by adjusting soil loss rates to be consistent with observed storms and with the rarity of the event in question. Another reason for the selection of the watershed modeling discharges was the ability to directly calculate frequency discharges for other locations within the San Marcos River watershed that do not coincide with a stream gage. The statistical frequency analyses support the watershed modeling results by demonstrating that they are within the confidence limits, especially for the 1% and 0.2% AEP events of interest for FEMA floodplain mapping.

Table 8.1: Recommended Frequency Flows for the San Marcos River Basin

Location Description	**50%**	**20%**	**10%**	**4%**	**2%**	**1%**	**0.40%**	**0.20%**
	2-YR	**5-YR**	**10-YR**	**25-YR**	**50-YR**	**100-YR**	**250-YR**	**500-YR**
Blanco River below Little Blanco	9,100	31,800	51,900	86,500	111,800	141,300	178,700	213,300
Blanco River at Wimberley	8,900	31,000	51,600	88,600	116,600	152,600	196,800	238,500
Blanco River near Kyle	8,600	30,300	50,700	88,100	116,300	153,900	199,300	244,900
Blanco River above San Marcos River	7,900	28,300	46,000	79,000	106,300	142,900	188,300	232,800
San Marcos River at San Marcos	310	1,380	2,530	4,100	5,160	7,860	14,800	21,100
San Marcos River below Purgatory Cr	950	2,720	6,640	12,000	17,200	23,100	31,400	40,300
San Marcos River above Blanco River	2,640	5,210	7,000	11,800	17,200	23,500	32,300	40,900
San Marcos River below Blanco River	8,800	29,900	48,500	82,400	110,500	153,600	205,500	255,900
San Marcos River above York Creek	8,400	27,600	45,800	75,900	100,200	136,500	182,200	237,900
San Marcos River below York Creek	8,800	29,400	49,000	80,100	105,500	144,100	194,000	257,100
San Marcos River at Luling	10,400	28,300	47,400	78,400	103,900	142,400	193,100	253,100
San Marcos River above Plum Creek	10,100	27,300	44,800	74,200	100,600	138,300	185,400	241,300
San Marcos River below Plum Creek	16,700	42,600	65,900	101,700	139,100	189,200	252,300	331,700
San Marcos Riv above Guadalupe R	13,900	38,000	56,700	91,000	128,000	178,200	239,700	304,600
Plum Creek at Lockhart	3,830	12,200	20,600	32,200	39,800	48,900	60,900	71,600
Plum Creek above Tenney Creek	5,700	13,900	18,800	26,200	39,200	53,900	74,400	91,400
Plum Creek below Tenney Creek	7,500	19,700	27,100	37,600	46,200	61,000	85,400	105,600
Plum Creek near Luling	6,600	17,700	29,600	45,900	60,600	78,600	106,300	132,100
Plum Creek above San Marcos River	6,800	18,300	30,600	47,200	62,300	80,700	108,900	135,100

9.0 Conclusions

Previous flood insurance studies for the San Marcos River Basin appear to have significantly underestimated the frequency discharges in most locations. The new flow frequency results are different from the effective flood insurance values because there have been new floods, that when included in the statistical hydrology, produce higher flows. In some cases, the statistically calculated flow values are higher than the results calculated with the watershed model. Additionally, the results of the rainfall-runoff watershed model exposed that some of the values calculated in the past using statistical hydrology were not reasonable and did not accurately reflect the response of the watershed to a 1% annual chance (100-yr) storm event. Because of the consistency achieved with the watershed modeling results, these are being recommended across the watershed. The statistical hydrology results, along with the gage records are being used to fine tune the watershed models, but ultimately, the watershed modeling results are considered to produce more reliable and consistent estimations of the flow expected during a 1% annual chance (100-yr) storm.

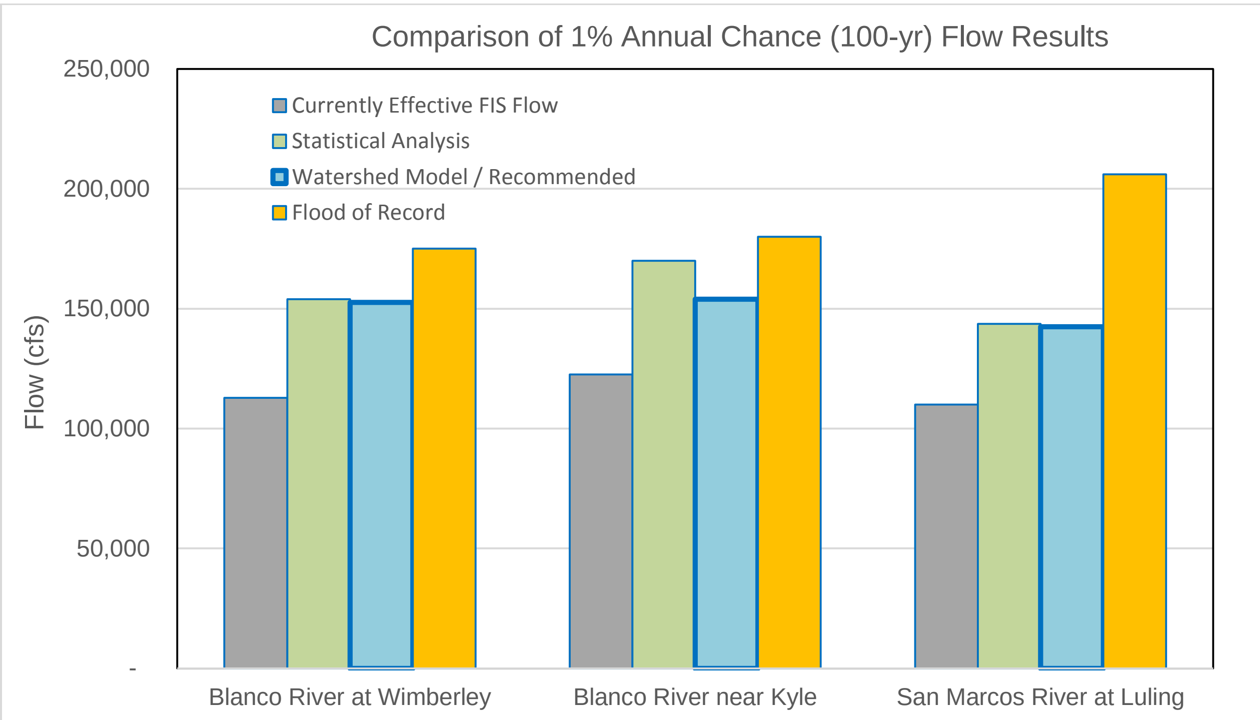

Figure 9.1: Comparison of 1% Annual Chance (100-yr) Flow Results

Given the severe loss of life and property that occurred during the May 2015 flood event, it is imperative that future updates to the flood insurance rate maps for the San Marcos River Basin accurately reflect the level of flood risk in the basin. The new flows represent the best estimate of flood risk for the Blanco River, San Marcos River, and Plum Creek based on a range of hydrologic methods performed by an expert team of engineers and scientists from multiple federal agencies. For the smaller tributaries, the new flows from the watershed model provide a good starting point which could be further refined by adding additional subbasins and using methodologies that are consistent with this study. The updated flows presented in this report can be used to revise flood insurance rate maps to help inform residents on flood risk impacts, which is important for the protection of life and property.

10.0 References and Resources

10.1. References

Asquith, W.H., *Effects of regulation on L-moments of annual peak streamflow in Texas*: U.S. Geological Survey Water-Resources Investigations Report 01–4243, 66 p., http://pubs.usgs.gov/wri/wri014243/; 2001.

Asquith, W.H., *Distributional analysis with L-moment statistics using the R environment for statistical computing*: Ph.D. dissertation, Texas Tech University, accessed on June 3, 2016 at https://ttu-ir.tdl.org/ttu-ir/handle/2346/ETD-TTU-2011-05-1319; 2011a.

Asquith, W.H., *Distributional analysis with L-moment statistics using the R environment for statistical computing*: CreateSpace, [print-on-demand], ISBN 978–146350841–8, [reprinting of Asquith (2011a), with errata]; 2011b.

Asquith, W.H., and Roussel, M.C., *Regression equations for estimation of annual peak-streamflow frequency for undeveloped watersheds in Texas using an L-moment-based, PRESS-minimized, residual-adjusted approach*: U.S. Geological Survey Scientific Investigations Report 2009–5087, 48 p., http://pubs.usgs.gov/sir/2009/5087/; 2009.

Asquith, W.H., Roussel, M.C., Atlas of *Depth-Duration Frequency of Precipitation Annual Maxima for Texas*; U.S. Geological Survey Scientific Investigations Report 2004-5041; 2009.

Asquith, W.H., Roussel, M.C., and Vrabel, Joseph, *Statewide analysis of the drainage-area ratio method for 34 streamflow percentile ranges in Texas*: U.S. Geological Survey Scientific Investigation Report 2006–5286, 34 p., 1 appendix, http://pubs.usgs.gov/sir/2006/5286/; 2006.

Asquith, W.H., and Thompson, D.B., *Alternative regression equations for estimation of annual peak-streamflow frequency for undeveloped watersheds in Texas using PRESS minimization*: U.S. Geological Survey Scientific Investigations Report 2008–5084, 40 p., http://pubs.usgs.gov/sir/2008/5084/; 2008.

England Jr., J.F., Cohn, T.A., Faber, B.A., Stedinger, J.R., Thomas Jr., W.O., Veilleux, A.G., Kiang, J.E., and Mason, R.R., 2016, *Guidelines for Determining Flood Flow Frequency Bulletin 17C*: U.S. Geological Survey Techniques and Methods, (in review).

FEMA, *Flood Insurance Study for Hays County, TX and Incorporated Areas*, FIS Number 48209CV001A, Revised September 2, 2005.

Good, P.I., and Hardin, J.W., *Common errors in statistics (and how to avoid them)*: New York, John Wiley, ISBN 0–471–46068–0, 2003.

Halff, *Lower Guadalupe River Basin Interim Feasibility Study – Phase 1, Technical Report Notebook (TRN) Appendix A - Topographic Data Development,* March 2014.

Halff, *Lower Guadalupe River Basin Interim Feasibility Study – Phase 1, Technical Report Notebook (TRN) Appendix D.1 Engineering Analysis –Hydraulics, Guadalupe, Blanco and San Marcos River Watersheds.* March 2014.

Halff, *Lower Guadalupe River Basin Interim Feasibility Study – Phase 2, Technical Report Notebook (TRN) Engineering Analysis – Hydrology and Hydraulics, Cypress, Bear, Upper San Marcos, Bypass, Plum, Mays, Peach and Spring Creek Watersheds.* May 2015.

Helsel, D.R., and Hirsch, R.M., Statistical methods in water resources: U.S. Geological Survey Techniques of Water-Resources Investigations book 4, chap. A3, http://pubs.usgs.gov/twri/twri4a3; 2002.

Interagency Advisory Committee on Water Data [IACWD], Guidelines for determining flood flow frequency: Bulletin 17B, Reston, Virginia, U.S. Department of the Interior, Geological Survey, accessed on May 10, 2016 at http://water.usgs.gov/osw/bulletin17b/dl_flow.pdf; 1982.

Judd, L., Asquith, W.H., and Slade, R.M., *Techniques to estimate generalized skew coefficients of annual peak streamflow for natural basins in Texas*: U.S. Geological Survey Water Resource Investigations Report 96–4117, 28 p., http://pubs.usgs.gov/wri/wri97-4117/; 1996.

National Centers for Environmental Information (NCEI), U.S. climatological divisions: National Oceanic and Atmospheric Administration, accessed on July 24, 2016 at https://www.ncdc.noaa.gov/monitoring-references/maps/images/us-climate-divisions-names.jpg; 2016a.

Nelson, Thomas L. “Synthetic Unit Hydrograph Relationships Trinity River Tributaries, Fort Worth-Dallas Urban Area,” 1970.

NCEI, Climate indices: National Oceanic and Atmospheric Administration, accessed on July 24, 2016 at http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp; 2016b.

NCEI, Historical Palmer Drought Indices: National Oceanic and Atmospheric Administration, accessed on July 24, 2016 at http://www.ncdc.noaa.gov/temp-and-precip/drought/historical-palmers.php and http://www.ncdc.noaa.gov/temp-and-precip/drought/historical-palmers/overview; 2016c.

NCEI, U.S. climate divisions—History of the U.S. climate divisional dataset: National Oceanic and Atmospheric Administration, accessed on May 10, 2016 at http://www.ncdc.noaa.gov/monitoring-references/maps/us-climate-divisions.php; 2016d.

Northwest Alliance for Computational Science and Engineering, 2016, PRISM Climate Group Data Explorer—Time series values for individual locations, accessed on May 10, 2016 at http://www.prism.oregonstate.edu/explorer/.

Palmer, W., 1965, Meteorological drought: U.S. Department of Commerce, Weather Bureau Research Paper 45.

Rodman, Paul K. “Effects of Urbanization on Various Frequency Peak Discharges,” 1977.

Slade, R.M., Tasker, G.D., and Asquith W.H., *Multiple-regression equations to estimate peak-flow frequency for streams in Hays County, Texas:* U.S. Geological Survey Water Resources Investigations Report 95-4019; 1995.

USACE. “Corps Water Management System (CWMS) Final Report for the Guadalupe River Watershed.” November 2014.

USACE. Engineer Manual 1110-3-1411, “Standard Project Flood Determinations.” Available from: http://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_1110-2-1411.pdf

USACE. “Flow Frequency Analysis for the Blanco River at Wimberley and Kyle, Texas in Response to the May 2015 Flood Event.” Technical Memorandum, dated September 25, 2015.

USACE. “SWFHYD “NUDALLAS” Documentation,” 1989.

U.S. Geological Survey, 2014, *PeakFQ—Flood Frequency Analysis Based on Bulletin 17B and recommendations of the Advisory Committee on Water Information (ACWI) Subcommittee on Hydrology (SOH) Hydrologic Frequency Analysis Work Group (HFAWG)*: accessed on May 7, 2016 at http://water.usgs.gov/software/PeakFQ/.

U.S. Geological Survey, National Water Information System: accessed on April 20, 2016, at http://waterdata.usgs.gov/tx/nwis/; 2016.

U.S. Geological Survey, *Computation of annual exceedance probability (AEP) for characterization of observed flood peaks*: U.S. Geological Survey Office of Surface Water Technical Memorandum 2013.01 accessed on July 1, 2015 at http://water.usgs.gov/admin/memo/SW/sw13.01.pdf; 2012.

Veilleux, A.G., Cohn, T.A., Kathleen M. Flynn, K.M., Mason, R.R., Jr., and Hummel, P.R., *Estimating magnitude and frequency of floods using the PeakFQ 7.0 program*: U.S. Geological Survey Fact Sheet 2013–3108, 2 p., http://pubs.usgs.gov/fs/2013/3108/; 2013.

10.2. Software

ArcGIS, Environmental Systems Research Institute, Inc., ArcMap 10.2: Retrieved from http://www.esri.com/.

HEC-RAS, US Army Corps of Engineers, HEC-RAS 4.1: Retrieved from http://www.hec.usace.army.mil.

HEC-DSSVue, US Army Corps of Engineers, HEC-DSSVue 2.0.1: Retrieved from http://www.hec.usace.army.mil.

HEC-HMS, US Army Corps of Engineers, HEC-HMS 4.1: Retrieved from http://www.hec.usace.army.mil

HEC-GeoHMS, US Army Corps of Engineers, HEC-GeoHMS 10.2: Retrieved from http://www.hec.usace.army.mil

10.3. Data Sources, Guidance & Procedures

Environmental Systems Research Institute, Inc. (ESRI). United States National Boundary, County Boundaries, Street Centerlines.
Available from: http://www.esri.com/software/arcgis/arcgisonline/services/map-services

Environmental Systems Research Institute, Inc. (ESRI),
http://www.esri.com/software/arcgis/arcgisonline/map_services.html
ESRI Streetmap2D Image Service - ESRI basemap data, DeLorme basemap layers, Automotive Navigation Data (AND) road data, U.S. Geological Survey (USGS) elevation data, UNEP-WCMC parks and protected areas for the world, Tele Atlas Dynamap® and Multinet® street data for North America and Europe and First American (CoreLogic) parcel data for the United States.
ESRI World Imagery Service - Imagery from NASA, icubed, U.S. Geological Survey (USGS), U.S. Department of Agriculture Farm Services Agency (USDA FSA), GeoEye, and Aerials Express.
ESRI. ArcGIS software. Application reference available from: http://www.esri.com/

Federal Emergency Management Agency (FEMA). Publication 64, "Federal Guidelines for Dam Safety, Emergency Action Planning for Dam Owners," Federal Emergency Management Agency (FEMA) U.S. Department of Homeland Security (DHS), Washington, D.C., 2004.
Available from: http://www.fema.gov/library/viewRecord.do?id=1672

Gesch, D., Oimoen, M., Greenlee, S., Nelson, C., Steuck, M., and Tyler, D. "The National Elevation Dataset: Photogrammetric Engineering and Remote Sensing," v. 68, no. 1, p. 5-11, 2002.

USACE. Engineering and Construction Bulletin 2008-10, CECW-CE, March 24, 2008.

USACE. Guideline RD-13, "Flood Emergency Plans -- Guidelines for Corps Dams," USACE Hydrologic Engineering Center, Davis, CA, June 1980.
Available from: http://www.hec.usace.army.mil/publications/pub_download.html

USACE, HEC. HEC-GeoRAS software.
Available from: http://www.hec.usace.army.mil/software/hec-ras/hec-georas_downloads.html

USACE, HEC. HEC-RAS software.
Available from: http://www.hec.usace.army.mil/software/hec-ras/hecras-download.html

USACE, HEC. “HEC-GeoRAS User’s Manual,” Davis, CA, September 2005.

USACE, HEC. “HEC-HMS Hydrologic Modeling System User’s Manual,” USACE, Davis, CA, November 2006.

USACE, HEC. “HEC-RAS River Analysis System, Hydraulic Reference Manual,” Davis, CA, November 2002.

USACE, HEC. “HEC-RAS River Analysis System User’s Manual,” Davis, CA, November 2006.

U.S. Department of Agriculture, Farm Service Agency. National Agriculture Imagery Program Images. Available from: http://www.fsa.usda.gov/FSA/apfoapp?area=home&subject=prog&topic=nai

U.S. Geological Survey (USGS). National Elevation Dataset. Available from: http://ned.usgs.gov/

U.S. Geological Survey (USGS). National Hydrography Dataset. Available from: http://nhd.usgs.gov/data.html

11.0 Terms of Reference

BFE	base flood elevations
cfs	cubic feet per second
CWMS	Corps Water Management System
DDF	Depth Duration Frequency
DEM	digital elevation model
DSS	data storage system
EM	Engineering Manual
EMA	expected moment algorithm
FEMA	Federal Emergency Management Agency
FIS	flood insurance study
GeoHMS	Geospatial Hydrologic Model System extension
GIS	geographic information systems
HEC	Hydrologic Engineering Center
HMS	Hydrologic Modeling System
IACWD	Interagency Advisory Committee on Water Data
InFRM	Interagency Flood Risk Management
LiDAR	Light (Laser) Detection and Range
LOC	Line of organic correlation
LPIII	Log Pearson III
MMC	Modeling, Mapping, and Consequences Production Center
NAD 83	North American Datum of 1983
NCDC	National Climatic Data Center
NED	National Elevation Dataset
NGVD 29	National Geodetic Vertical Datum of 1929
NHD	National Hydrography Dataset
NID	National Inventory of Dams
NLCD	National Land Cover Database
NMAS	National Map Accuracy Standards
NRCS	Natural Resources Conservation Service
NWIS	National Water Information System
NWS	National Weather Service
PDSI	Palmer Drought Severity Index
PeakFQ	Peak Flood Frequency
PMF	probable maximum flood
QPF	Quantitative Precipitation Forecast
RAS	River Analysis System
ResSIM	Reservoir System Simulation
RFC	River Forecast Center
SCS	Soil Conservation Service
SHG	Standard Hydrologic Grid
SI	Structure Inventory
SME	subject matter expert
SOP	Standard Operating Procedures
sq mi	square miles
SSURGO	Soil Survey Geographic Database
TLS	Total-Least Squares
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WCM	Water Control Manual
WGRFC	West Gulf River Forecast Center